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The feasibility of probability sampling in describing quality of rural water not affected by point sources is examined. The study site was a portion of the Chowan River Basin in Virginia and North Carolina. Flow was measured along with dissolved oxygen, temperature, conductivity, and pH. All samples were analyzed for nitrate plus nitrite nitrogen, total Kjeldahl nitrogen, total phosphate and chloride. Flow was highly variable in time and space; concentration was less so. For estimating basin-wide mean values with modest budgets, grab sampling was more flexible and provided better precision of estimation than did automated sampling under the same budget. With high-budget studies (several hundred thousand 1975 dollars) this relationship may be reversed. This comparison is stated on the restrictive basis of estimating mean values; automated sampling may have other advantages with other kinds of studies.

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PROBABILITY SAMPLING TO MEASURE POLLUTION FROM RURAL LAND RUNOFF

by

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FOREWORD

Environmental protection efforts are increasingly directed towards preventing adverse health and ecological effects associated with specific compounds of natural or human origin. As part of this Laboratory's research on the occurrence, movement, transformation, impact, and control of environmental contaminants, the Environmental Systems Branch studies complexes of environmental processes that control the transport, transformation, degradation, and impact of pollutants or other materials in soil and water and assesses environmental factors that affect water quality.

Nonpoint sources contribute significantly to water pollution problems in many areas of the United States. Because of this, more information is needed on rural nonpoint sources to guide the development of pollution control strategies that may be required. Sound information, however, rests on the development of accurate, cost-effective sampling methods. This report investigates the use of probability sampling, a technique that has been widely applied to many scientific and social problems, to describe rural water quality and evaluates the costs of this sampling method.

David W. Duttweiler
Director
Environmental Research Laboratory
Athens, Georgia

ABSTRACT

Our objectives were to investigate the feasibility of probability sampling in describing quality of rural water not affected by point sources and to study the substantive results. We defined a rural nonpoint source as the output of a small measurable subbasin that did not contain a point source.

The study site was in a portion of the Chowan River Basin in Virginia and North Carolina. Sampling was in space and in time. In space, four convenient subareas were used; within each, primary sites were chosen at random (total 15), four also had automated samplers and stage recorders. Two sampling times were selected at random from each four-week time stratum.

Flow was measured on all visits along with dissolved oxygen, temperature, conductivity, and pH. Water samples for chemical analysis were iced for grab samples and acidified for samples from the stage-activated automated samplers. Samples for kinetic studies were iced and those for algal studies were kept at ambient temperature.

All samples were analyzed for nitrate plus nitrite nitrogen, total Kjeldahl nitrogen, total phosphate and chloride (these data subject to more intensive statistical examination). Chemical oxygen demand, total organic carbon, orthophosphate, ammonia, and suspended solids were analyzed on a reduced schedule.

Costs of a one-year sampling study were estimated (in 1975 dollars) for grab sampling as: constant (overhead) costs, \$14,211.25; per-site costs, \$153.18; and per-visit costs, \$79.47. For automated sampling the constant cost was \$14,438.09; the per-site cost was either \$5,667.38 or \$7,277.30, depending upon whether weekly service trips were accounted as per-visit or per-site; per-visit cost was correspondingly \$149.01 or \$32.89.

A statistical error of estimation was synthesized; to stabilize the variance and to provide additivity of effects, analyses were under logarithmic transformation with precision of estimation stated as proportional standard error. Comparisons were on the basis of relative precision under a constant budget.

Flow was highly variable in space and time; concentration was less so. Stating precision as proportional standard error for a \$55,000 grab sampling study with optimal allocation, concentrations were measurable with fair precision (0.08-0.17); flow and transport were not (0.50-0.95) although adjusting for area (to yield) somewhat improved the precision

(0.41-0.88). Precision was increased (variance reduced) with larger sample size (and greater cost) more in proportion to the square root of the increase rather than directly. Thus, improved precision is costly.

For estimating basin-wide mean values with modest budgets, grab sampling was more flexible and provided better precision of estimation than did automated sampling under the same budget. With high-budget studies (several hundred thousand 1975 dollars or more) this relationship may be reversed. This comparison is stated on the restrictive basis of estimating mean values; automated sampling may have other advantages with other kinds of studies.

Optimal allocation, while improving precision, differed with parameter. An empirical rule-of-thumb based on this study suggests that the number of sites sampled may be made approximately equal to the number of sampling visits made annually to each site.

The algal community, of many species, was usually low in biomass, with fluctuations to be explained by changes in algal input processes rather than by growth. Growth was limited by high flushing rates and poor light, but not by nutrients. Potential growth limitation was most frequently by nitrogen.

The grab sampling data revealed no clear relationships between water quality parameters and macro land-use factors. Channelized streams had elevated concentrations of nitrate plus nitrite nitrogen. Measured concentrations did not display consistent functional relationships to flow. Water yields and associated nutrient yields were greater during winter and spring. The potential that daily weather predictions might be used for stratification in time to reduce the effect of high flow variability was presented.

Laboratory oxygen kinetic studies indicated that organic material entering these streams is relatively unavailable to indigenous organisms, a fact consistent with high in-stream levels of dissolved oxygen. Average rural stream water quality was relatively uniform for the 18-month period and generally good compared to proposed standards. However, elevated concentrations of total phosphate even in the forested Piedmont areas demonstrated the need for basing water quality assessments on local background or natural levels.

This report was submitted in fulfillment of Grant #R803328-03-4 by North Carolina State University, Biological and Agricultural Engineering, under the partial sponsorship of the U.S. Environmental Protection Agency. This report covers a period from July 1, 1974 to December 31, 1978, and work was completed as of October 1, 1979.

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SECTION 1

CONCLUSIONS

STATISTICAL PROCEDURES AND RESULTS

Conclusions of this study must be drawn within the constraints of our basic assumptions: that we are to determine water quality for the output of small drainage subbasins as river-basin averages of such quantities as concentrations of chemical parameters, or rates of flow or transport or yield of water or chemicals; that reference is to a one-year study; and that the basic objective is the most precise information for the available budget. In these terms, these conclusions follow from our study of a portion of the Chowan River Basin.

When identified as the output of small drainage subbasins, rural runoff can be measured by use of probability sampling in space and time. Concentrations were measurable with good precision. Flow and other measures, such as transport or yield of chemicals which included the flow as a component, were not measurable with good precision, although adjusting flow or transport to yield by taking account of basin area improved precision somewhat. These conclusions hold whether grab sampling or automated is to be used.

Precision was difficult to attain for flow or related measures for two reasons. First, there was high inherent variability both in space among small drainage subbasins and in time at any site. Second, and this is true also of measuring concentrations, sampling was required in two dimensions; and because both the space and time components of variance were important, neither was reduced in direct proportion to increased total sampling effort. Rather, each and their sum was reduced in rough proportion to the square root of the total sampling effort. Thus, for flow not only was the variability inherently high, but precision responded slowly to increased sampling effort. For concentrations, the variability was not so high and better general precision could be attained even though the same requirement for two-dimensional sampling existed as an impediment when attempting to increase precision. These problems concerning variability exist by the nature of sampling river basins; they do not arise because probability rather than judgment sampling is used.

We found that grab sampling promised better precision than automated sampling for the same cost at modest budgets. Grab sampling is more flexible and adjusts easily to the need for more sampling in space. In comparison, automated sampling is costly for sampling in space but provides low-cost sampling in time at any site where installed. Speculation suggested that automated sampling would generally become more cost effective than grab sampling at high budgets (several hundred thousand 1975 dollars or higher).

We found stratification in time generally worth the effort in terms of increased precision, but it is possible to over-stratify and reduce efficiency by planning too-frequent visits to too-few sites.

Optimal allocation of sampling effort is important to efficiency and may be calculated given information on costs and variances. We found, however, that optimal allocation differs with the parameter. Because a survey can rarely be planned for a single parameter, this means that the sampling effort must be allocated to be of median efficiency on the average but probably near optimal for only a few parameters. Based on our experience, such a compromise design might have the number of sites sampled approximately equal the number of visits per year to each site, although this entirely empirical suggestion must be re-examined when more information is available.

ALGAL POPULATIONS IN TWO SMALL STREAMS

In two small streams the algal community included many species with only a few dominant forms.

Algal biomass was usually low but reached high levels occasionally. Explanation for fluctuations in biomass must be sought in processes bringing algae into the flowing water from the bottom or from nearby water or land, rather than in growth of the ambient plankton itself.

Algal population levels in these headwater streams are limited by fluctuations in these unknown input processes, by high flushing rates, and possibly by poor light, not by nutrients; ambient populations are only a fraction of the potential levels realized in laboratory assay and possibly in lower parts of the same stream.

Algal assays indicated potential growth limitation most frequently by nitrogen, next by factors other than nitrogen or phosphorus, rarely by phosphorus alone. Such potential limitations apply in reality only at some hypothetical downstream location and condition, not to populations present in these small streams.

Within-stream fluctuations in potential nutrient limitation suggest a within-stream heterogeneity in nutrient balance.

GRAB SAMPLING WATER QUALITY INTERPRETATIONS

Grab sample data from a two-year, statistical sampling study in arbitrarily selected areas of the forested and agricultural Piedmont, plus well- and poorly drained Coastal Plain, all in the Chowan River Basin, were analyzed to permit a clearer understanding of the nature of rural runoff on an areawide basis. These analyses provided the following conclusions:

> Neither in-stream (arithmetic average) nor net export (flow weighted) concentration data presented any clear relationships between water quality and macro land-use factors. This result points out the need for caution when employing model predictions

to specific cases. Macro land-use factors do not account for varying agricultural cropping and management practices, annual weather conditions, stream border buffer systems, or other factors which can minimize the impact of agricultural activities on water quality.

The impact of channelizing Coastal Plain streams was most pronounced with respect to elevated NO_3-N concentrations in these streams as compared to unchannelized streams which have natural swampy flood plains and channels which increase NO_3-N attenuation by denitrification and biological uptake.

Analyses for seasonal trends indicated that water yield and the associated nutrient yields were greater during the winter and spring seasons than during the summer and fall seasons reflecting rainfall and evapotranspiration cycles. The model to evaluate relationships between flow weighted concentration and both season and land use showed that TKN and TP concentrations were related to season and NO_3 concentrations to both season and flow but associated r^2 values were low.

Measured concentrations did not display any consistent functional relationship to flow (water yield) levels. However, data showed that NO_3-N concentrations were elevated during flow conditions at a small (0.50 km^2 or 0.2 mi^2) site but not at larger (20 km^2 or 8 mi^2) sites in the well-drained Coastal Plain with similar land use. The NO_3-N attenuation was judged to be the result of in-stream dynamics.

Comparisons of geoclimatic areas demonstrated that the dominant variation was between the Piedmont and Coastal Plain with only relatively minor variations occurring within these two physiographic regions. The differences between the Piedmont and the Coastal Plain were judged to be due to naturally occurring physiographic variations in (a) basin characteristics, such as vegetation, soil type, and steam hydraulics; and (b) ocean proximity.

The heterogeneous land-use mix and vegetative borders around receiving streams characteristic of the Southeast in conjunction with different geoclimatic conditions for studied regions are major factors in obscuring clearer relationships between land use and water quality for the investigation intensity employed.

Results from laboratory oxygen kinetic studies indicated that organic material entering these streams from rural inputs is relatively unavailable to indigenous organisms, a fact further verified by the high in-stream mean dissolved oxygen levels.

Assessment of point and nonpoint source impacts in one small basin verified classic point source concentrations spikes with subsequent decline to intermediate levels for all investigated constituents except chloride and nitrate. Therefore, for the stream reach studied, nitrogen and phosphorus inputs which appear to come from treatment plant effluents are reduced to headwater background levels as long as the stream assimilatory capacity is not overwhelmed or natural inputs do not result in changed background water quality.

Point-in-time comparisons between headwater and downstream chemical parameters showed small differences.

Comparison of annual water yield estimates from the 15 statistical survey sites to historic values for the study region verified that simple time stratified (STS) grab sampling provided an unbiased estimate of areawide annual water yield; however, the precision of the individual estimates was low. Sampling theory indicates that increased estimate precision of heterogeneous populations, such as measurements of water yield, can often be achieved by stratification. Thus, the potential of employing daily weather predictions as a means of time stratification to improve water yield estimate precision at a given sampling intensity was reviewed.

Eighteen-month average rural stream water quality for the four geoclimatic areas was relatively uniform. The quality was generally good compared to proposed standards, but elevated TP concentrations even in the forested Piedmont area demonstrated the need for basing water quality assessments on measured local conditions, especially background or natural levels. Stream sample concentrations usually displayed large variations indicating that rural nonpoint sources are highly variable in both space and time.

WATER QUALITY DATA COMPARISONS FOR GRAB AND AUTOMATED SAMPLING

Statistical sampling methods can be employed to measure the mean areawide contribution of chemical species from rural nonpoint sources as an alternative to the more difficult and often impractical complete monitoring approach. Grab sampling and automated sampling are two common methods of assessing stream water quality that can be employed in a statistically designed sampling program. Automated data was collected at 5 of the 15 grab sites. Long-term grab data were obtained from November 24, 1974 to March 19, 1977, and automated data from May 18, 1975 to March 19, 1977. All automated and grab sampling sites were operational from March 21, 1976 to March 19, 1977. During these periods substudies were conducted to investigate particular sampling methodologies. The resulting data comparisons for grab and instrument sampling support the following conclusions:

Point-in-time comparisons of manually depth integrated and fixed point automated samples were conducted for COD, TOC, TP, TKN, NO_3-N and Cl. One substudy showed that manually depth integrated samples provides lower estimates of COD, TOC, TP, TKN, and Cl concentrations (36, 39, 28, 18 and 8 percent, respectively) than the first sample obtained from fixed point automated samplers in routine stage-activated operation when both samples were preserved by refrigeration until laboratory analysis.

Data from a study to determine the relative contribution of sample procurement, preservation, and storage on automated sample parameter concentrations indicated that the sample-flush sampling cycle produced a "first" sample effect; that is, the first sample obtained from a sampling which was inactive for approximately a week had about 60 percent higher concentrations of COD, TOC, TP, and TKN than samples taken immediately thereafter. About 20 percent lower concentrations of COD and TOC were observed for manually depth integrated samples preserved by cooling compared to fixed point automated sample preserved by acid fixation. Finally, acid-fixed automated samples which were stored in the field for a week had about 20 percent lower COD and TOC concentrations than acid-fixed automated samples returned immediately to the laboratory for analysis. These data indicate that COD and TOC were the parameters impacted most when recommended procedures were employed in routine data acquisition. Furthermore, the sample-flush cycle caused a first sample effect that had a significant impact on several parameter concentrations.

Annual volume average concentration and water yield estimates were obtained at four sites by routine operation of both stage-activated automated samplers with stage recorders and simple time stratified grab sampling. Results indicated that about 50 percent lower COD, TOC, and TP estimates were obtained by the grab sampling method. Although rather large differences were observed for the water yield estimates, the data did not indicate any statistically significant difference between the two methods. Due to confounding factors associated with the two sampling methodologies, it was not possible to specifically define the source of the concentration differences.

SECTION 2

RECOMMENDATIONS

STATISTICAL PROCEDURES AND RESULTS

Probability sampling in space and time should be employed when determining river basin average values, in particular, averages of the contribution of small headwater subbasins to a river system.

For short-term (ca. one year) studies under modest budgets (less than 100,000 1975 dollars), the use of grab sampling methods should be given serious consideration on the basis of cost effectiveness. The longer and more costly the study, the more the balance shifts toward favoring automated sampling, especially in studies of flow, transport, and yield.

A purely empirical suggestion, based upon current information, is that in such a one-year study based on grab sampling, the sample number of sites should be approximately equal to the number of annual visits made to each site. This rule-of-thumb must be reexamined with a broader data base.

Time strata should be delineated in such a one-year survey design after the number of visits has been determined, with two visits per time stratum. Relatively good precision may be expected of sampling studies of concentrations.

ALGAL POPULATIONS IN TWO SMALL STREAMS

The origin of planktonic algae in small headwater streams should be further studied to determine the relative contribution from the periphyton, from bodies of standing water, and from the soil surface.

WATER QUALITY INTERPRETATIONS

Statistical sampling methods can be employed to measure the mean areawide contribution of chemical species from rural nonpoint sources as an alternative to the more difficult and often impractical complete monitoring approach. Grab sampling and automated sampling are two common methods of assessing stream water quality which can be employed in a statistically designed sampling program. Water quality based results of the grab and automated sampling comparisons provide information which can be utilized to design sampling plans that minimize the variance attributable to sampling methodology.

Interpretation of data and experiments to compare grab and automated sampling procedures led to the following recommendations to reduce noted result differences:

> A flush-sample cycle rather than a sample-flush cycle should be employed with automated sampling so that material that may have settled or grown in the sampler intake can be expelled before a sample is obtained. This should minimize the elevated first sample TOC, TP, and TKN concentrations that were observed with the sample-flush operational mode. However, data are needed to determine the extent to which a flush-sample cycle may reduce this bias.
>
> Chemical preservation techniques should be considered when refrigeration is not feasible. If acid-fixation is employed, field storage time should be as short as possible in order to minimize chemical oxidation of the organics that can reduce TOC and COD concentrations.
>
> The relative impact and potential interactions of a fixed intake for automated samplers versus depth integrated grab samples, as well as different storage and preservation techniques upon both soluble and filterable type constituent measurements, needs further examination.

The effect of sampling methodologies on water quality measurements in no way lessens the need to establish adequate data bases in order to provide a foundation for sound scientific assessment of rural nonpoint sources. The information presented should aid future investigators and monitoring agencies in better understanding stream monitoring data and designing improved data acquisition systems.

The relatively similar arithmetic average concentrations for sampling sites receiving rural inputs from different land use and geoclimatic regions, and in the main river draining these sites, indicate that more data on background conditions and relative impact of nonpoint sources are needed before widespread implementation of best practices is required, particularly in areas with heterogeneous land use. It also seems most important that agencies developing regulatory criteria be responsive to ambient conditions and not entertain standards requiring better than background water quality, particularly for relatively undisturbed or pristine areas such as the forested region of this study basin.

SECTION 3

STUDY SYSTEM

PROJECT SCOPE

We undertook this study in response to the growing demand for information on the influence of rural nonpoint sources on water quality. Policy makers need this information to define the status of rural nonpoint sources, to guide control strategies (if required), and to provide data for model development. Further, a method for cost analysis of various methods and designs for sampling is required to guide efficient measurement.

The objectives of our study were to investigate the feasibility of using probability sampling in describing rural water quality not affected by point sources on a river basin-wide basis and to examine the substantive results of this sampling effort for insight on currently important questions. These objectives required that we define a rural nonpoint source; in this study we have taken this to be the output of a small measurable subbasin that does not contain a point source.

Appraisal of water quality in these very small drainage units of a complete river basin requires that sampling be used, both in time and in space. The cost of the continuous coverage of every such small basin in even one river drainage would be prohibitive; partial (sampling) information must be used. Sampling may be carried out either as judgment sampling or as probability sampling; our objective was to explore use of the last.

Historically, judgment sampling has dominated the study of water quality. Sites and times for sampling are selected by professional judgment as typical of the kind of stream being studied. The process is characterized by subjective judgment in selection of the study material and in this fact lies both the strength and the weakness of the method.

The advantages of judgment sampling are that the sites and times chosen for sampling study can be selected by the investigator according to his experience and judgment as those that he considers best suited for the program needs, technical requirements, and best use of sampling resources. The disadvantages of the system are the introduction of personal bias in the selection process, the difficulty of defining a sampling error, the fact that the selection process is not reproducible by another investigator because of the personal element, and the fact that the results cannot be extrapolated for lack of a defined universe. Thus, such studies must remain a series of special cases.

Probability (or random) sampling has not been much used in the study of water quality. Here, after a rigorous definition of the scope of the problem, the sites and times of sampling are selected with known probability from a list (frame) of all possible. Often in defining the larger problem it may be subdivided (stratified) into smaller nonoverlapping but all-inclusive parts, each of which is sampled independently.

Probability sampling has been widely applied to many scientific and social problems. Its advantages are that unbiased estimates may be derived by methods that are reproducible; that inference may be made from the sampling results to the defined universe; that statistical sampling error can be estimated; and that with certain assumptions about statistical distribution, confidence limits may be set about the estimates. The ability to estimate sampling error provides a rational basis for considering the optimal allocation of sampling effort.

Disadvantages of probability sampling are that without effective stratification, too much of the field effort for maximum efficiency may be spent at the more numerous sites and times of generally low flow. Some randomly selected sites may seem "nonrepresentative" to the field man (but every site is unique in some way). Some randomly selected sites cannot be sampled (but such sites should not have been included in the sampling frame if they cannot be studied). Semi-synchronous sampling will generate correlations among site records (but this may be true of judgment sampling as well).

Either an automated installation or grab (hand) methods may be used to take water samples and measure flow. Either method may be used with judgment sampling or with probability sampling. An automated installation is costly, but it can provide a continuous record of stream flow and a programmed series of water samples. Grab sampling costs less per site sampled and is therefore a more flexible method when covering many sites, but it provides information about flow and water quality only for the time of the technician's visit. We investigated both methods to determine which was the more cost effective for use with probability sampling under conditions of our study.

The cost of information determines the scope of any appraisal of water quality. Demand for the information has risen faster than the budgets for obtaining it, and therefore the most cost-effective sampling plan should be used for the measurements whether they are made by automated or by grab methods. To determine cost effectiveness some criterion of effectiveness is needed; we have used precision of the estimate, a concept widely applied in sampling surveys. By examining the variance components, we may judge whether better precision can be attained; for example, by using more sites and making fewer measurements at each, or by making more measurements at fewer sites, with the same budget in either case. The approach required that we make an analysis of all the costs of an investigation of water quality using probability sampling.

The data gathered in this study have also been examined for the information they provide on water quality in the selected portions of this single river basin. Thus the field data, which were necessary for the feasibility study, served a dual role in also providing insight to rural water quality.

This analysis included the information from studies of algal populations and on other project substudies, as well as on water quality and land use.

FIELD EQUIPMENT AND PROCEDURES

Grab

Efforts were focused in this study on obtaining the most reliable physical and chemical data possible within given time and manpower restraints. However, because this was a feasibility study of a methodology which might be adopted by other agencies rather than a pure research effort to characterize a system, extensive site preparations or modifications for sampling were not undertaken. Additionally, extensive physical modification of a natural stream, especially an elaborate control structure, might well cause changes in the stream's flow regime and quality, such as ponding in a weir pool with a concomitant settling of particulates and absorbed nutrients.

Grab sampling was initiated on November 24, 1974. Prior to this time procedures for making each measurement were established after which field crews were trained. Routine grab sampling was terminated on November 27, 1976. This afforded a full two-year data record for all sites. The overall stream side procedure is separated into three steps: (1) Make water quality measurements, (2) obtain water quality sample, and (3) measure stream flow. This order is important, particularly in slow flowing Coastal Plain streams because dislodging bottom sediments by walking in the stream bed would cause spurious results. The water quality measurements were made from the bank on small streams or from a bridge on large streams.

Quality control was given considerable attention during the course of this study, including field procedures. All technicians were given identical training following a detailed written outline to ensure that all measurements were made in the same manner. Additionally, retraining sessions were held bimonthly to ensure that all personnel were using consistent methods.

All meters and instruments were subject to routine maintenance. The schedules and steps for each piece of apparatus were written out and each technician was assigned specific tasks to perform. A checklist aided in establishing timely attention. This was of great benefit in minimizing breakdowns and loss of data.

Flow--

Because stream flow was felt to be the least precise measurement made, attention was focused on obtaining the best estimates possible. Two general stream types were present, Piedmont and Coastal Plain. The Piedmont streams in general have well-defined channels and velocities in a range suitable for current meter measurement. The Coastal Plain streams were in general sluggish and had poorly defined channels except in those areas where channelization had occurred. These streams were extremely difficult to measure.

For the most part, methods recommended by the United States Geological Survey (USGS) were employed in making flow measurements. Extensive use of sand bags to construct restricted measuring sections was employed where velocities were below detention limits, as well as permanent modifications at some stations. These modifications are described in the section on site description.

Price Meter--A Price meter manufactured by the Weathermeasure Corporation was employed during the course of this study. This meter has the advantage of electronic readout directly in meters per second rather than the method of generating clicks and amplifying them to a head phone while simultaneously recording time intervals with a stop watch. The meter was routinely checked during the course of the study; both upper and lower bearings, as well as a cup wheel, were replaced about midway through the data collection. Following this the calibration was checked against two other meters. No deviation from the original rating curve was noted, within the precision obtainable. The Price meter had a somewhat higher starting velocity than the Ott meter, and therefore was used only when the stream could not safely be waded. In general, the meter performed in a satisfactory manner.

Ott Meter--The Ott meter is a horizontal shaft instrument manufactured in Germany and has proven ideal for measuring the small, slow flowing streams in this study. The meter was equipped with the optional component propeller which automatically accounts for angularity of flow. In addition, this propeller has a lower limit of about 3 cm/sec for reliable measurement. The meter is used with an electromechanical counter in conjunction with a stop watch and greatly reduces possibility of human error in comparison with the method of manually counting clicks.

Pigmy Price Meter--The Pigmy Price meter had a much higher starting speed than the Ott meter and in addition, because of low velocities, it was extremely difficult to determine the angle of flow. This meter used the clicks-count method for velocity measurements with attendant higher chance of human error. It was felt that this meter was much less suitable than the Ott meter under identical conditions, and therefore the meter was used only in a back-up role.

Float Measurements--On many occasions, velocities, even in restricted sections, were too low to measure by current meter methods. In addition, on several occasions the level of water was too low to submerge the meter in the stream. Under these conditions float measurements were made, generally with small wooden sticks over a 2 to 3 m (5 to 10 ft) section.

Volumetric Measurement--Volumetric measurements were sometimes possible using a calibrated bucket and stop watch. This technique is perhaps the most precise used; but its application is limited since there must be a place to position the bucket to catch the flow, and the upper limit of flow per measuring point is about 10 liters per second. Several measurements can be made across a flow drop, but this substantially reduces the precision of the measurement.

Estimation Method--When conditions precluded any of the preceding procedures, estimation methods were employed. This was generally true under extremely low flow conditions. The technique employed was to create a small shallow channel and then to visualize the filling of an appropriate sized bottle over a one-minute period. Field crew training was accomplished by utilizing troughs in the chemical laboratory and after some practice flows could be estimated to within 10-15 percent.

Stage--

At the time the stream flow measurement was taken, stage was recorded for development of a stage-discharge relationship. This served two functions. First it provided an alternate low cost stream flow measuring technique after the stage-discharge relation was developed, and second it established a historic data base pursuant to translation of stage recorder data to stream flow estimates at the automated sites.

Physio-Chemical Measurements--

Dissolved Oxygen--All dissolved oxygen (DO) measurements were made using a commercial polaragraphic type instrument, calibrated before each measurement with air saturated water. Distilled water was used for the calibration and was kept in the back of the field van in order to maintain the calibration temperature with 5 °C (9 °F) of the stream temperature. Where this was not the case, the sealed calibration bottle was placed in the stream and allowed to equilibrate until it was within 5 °C (9 °F) of the stream temperature. Previous experience in our laboratory and many others has shown close agreement with the Winkler-Azide method, and therefore no further comparisons were made during the present study. The measurement was made at approximate mid-depth in the center of flow of the stream. Experiments showed that occasionally in eddys at the side of the stream low DO measurements were recorded. Therefore, this situation was always avoided. As with all instruments used in the study, routine maintenance was accomplished by following a written schedule. One problem experienced was fouling of the membrane by dissolved organic constituents in Coastal Plain streams. Apparently some constituents crossed the membrane and over a period of time poisoned the cathode; subsequently a new probe was put into service.

Temperature--Temperature was measured both as a parameter and for calibrating various instruments. Initially all meters used were compared to carefully calibrated laboratory thermometers. Discrepencies were noted and a correction was made for each meter. Periodically this correction was rechecked against the laboratory thermometer.

Conductivity--Measurements were made using a commercial field model of the standard Wheatstone bridge meter with the cell encapsulated in plastic. The measurement was made at approximately the same stream position as the dissolved oxygen measurement. Before each field trip the instrument was calibrated with 0.1 normal potassium chloride solution at 25 °C following the manufacturer's specifications. As with the dissolved oxygen meter, the cell apparently was fouled by the high level of dissolved organic materials in the Coastal Plain streams; and therefore, the cell was periodically cleaned using the manufacturer's recommended method.

pH--Measurements were made using a commercial field pH meter. The meter was calibrated before each use against buffers of pH 4 and 7. Once again, dissolved organic materials appeared to cause interferences with the measurement and assumedly were fouling the glass membrance of the pH electrode. Therefore, whenever proper calibration against the two buffers was not possible, the electrode was cleaned following the manufacturer's recommendations and then recalibrated. All measurements were made at mid-depth at the center of flow.

Sample Procurement--

Chemical Samples--Grab samples were obtained using a manually-depth integrated method at the center of flow. An early experiment had shown that cooling to a temperature of below 4 °C was an acceptable preservation method for all parameters measured. All samples were collected and stored in preaged, acid-washed plastic bottles. Immediately after collection all samples were placed in ice and kept cold until analyzed in the laboratory. An early experiment had shown that there was no observable difference in values for tests to determine nitrogen, phosphorus, and oxygen demand between manually depth integrated sampling and using a more sophisticated depth integrating sampler. Therefore, the manual depth integrating technique was used throughout the study.

Sediment Samples--As with the chemical samples, the sediment samples were taken using a manually depth integrated technique. Calibration with a USGS DH-49 depth integrating sampler had shown no significant differences. Because of the size of sampled streams, samples were generally taken at only one vertical in the center of flow. These samples were also iced and refrigerated until analysis.

Algal Samples--Two types of algal samples were collected. One type was for a productivity study and the second type was for characterization of standing populations. Those collected for productivity studies were treated in the same manner as the sediment and chemical samples. Those collected for characterization of the standing populations were fixed immediately after collection by adding 30 milliliters of Lugol's solution to a 200 milliliter water sample in an opaque brown bottle. These samples were not iced but kept at ambient temperatures.

Kinetic Samples--These samples were designated to be run for biochemical oxygen demand (BOD) and oxygen uptake studies as well as nutrient recycling studies. Because of this, care was taken to ensure that the bottles were completely filled with water and all air was excluded. As above, all samples were iced and refrigerated until analyses.

Automated Sampling

One of the prime reasons for installing the automated sites was to make a comparison of continuous stage recording versus grab sampling. A second was to study transport characteristics during runoff events. It was also hoped that these sites might serve as "field truth stations" to assess the overall effectiveness of the grab sampling scheme. All instrumented stations were operational on July 19, 1975, and operation was ceased on March 19, 1976, affording an 18-month data record. Grab sampling was continued at these sites after November 17, 1976, to have comparable data records.

Stage Recording--

Continuous stage was recorded on an analog recorder and later transformed to digital computer input form. A stilling well and instrument house were installed with design assistance from local USGS personnel. Initially, natural controls were used at all five sites. However, stream bed shift problems were experienced early in the study, and at three of the five sites low height artificial controls were installed to better define the stage discharge relation under base flow conditions. Because flow was measured at each grab sampling visit, there were as many as 52 observations for establishing a stage discharge relation. As personnel schedules allowed, additional visits were made during storm events to secure high flow data.

At one Piedmont site there was an active beaver colony. The dams were removed in an effort to discourage the colony; however, they were soon rebuilt. Virginia officials cooperated in trapping these beavers and once again the dams were removed. However, soon thereafter a new colony of beavers began establishing dams below the instrument station. Eventually this site had to be abandoned because of beaver activities and the resulting continuous change in the stage discharge relationship. This might well be a frequent occurrence on small rural streams; and if beaver activity is noted in a proposed monitoring watershed, serious consideration should be given to selecting an alternative site.

Rainfall Measurement--

Rainfall intensity data was gathered using tipping bucket rain gages which were serviced weekly and these performed quite adequately. Initially attempts were made to gather quality data by catching rainfall in airlock sample containers. However, almost invariably it was discovered that foreign materials found their way into the sample. Therefore, these attempts to establish rainfall quality were abandoned early in the study. The tipping bucket rain gages were installed following recommendations of the National Oceanographic and Atmospheric Administration.

Automated Samplers--

Automated samples were obtained using a commercial sampler which collected up to 28 discrete samples. The sampler was activated by stage change with a subsample being taken at each 76 mm (3 in.) or fall in stream stage. Samples were collected in 500 milliliter plastic bottles. The bottles were precharged with sufficient sulfuric acid to bring the sample pH below 2. Early experiments had shown that acidification was an acceptable preservation technique for the parameters measured in this study. The sample time was recorded directly on the hydrograph by a subsidiary electronic circuit described in the following section, "Activation and Notation System."

Placement of the intake was a prime consideration. To avoid mechanical breakdowns which might be experienced with a moveable intake, a fixed intake was chosen. The intake body was located just beneath the low flow level in the stream. This assured that the intake would be submerged at the start of a stream rise, but also meant that the intake was near the bottom of the water column during high flow events.

The intake figuration was a cylinder about 150 mm (6 in.) long and 38 mm (1-1/4 in.) in diameter with about 30, 6.4 mm (1/4 in.) holes in the body. This cylinder was placed in longitudinal alignment with stream flow and was wrapped with fiberglass screen to prevent line clogging. Unfortunately, this screen proved to be a good substrate for algal growth and thus was cleaned weekly as part of the maintenance routine.

Activation and Notation System--

Because runoff events were deemed more important than baseflow conditions, samplers were activated on the basis of stage rather than time, and discrete rather than composite samples were collected to facilitate mechanistic interpretations. However, to obtain a complete as possible record, no minimum point for sample initiation was selected; and the primary interval for sample activation was made as small as practical (76 mm [3 in.]). Thus, a sample would be obtained during a period of baseflow recession when the stage dropped 76 mm (3 in.).

The sampler selected (ISCO Model 1392, Instrumentation Specialities Company, Lincoln, Nebraska) may be activated on a time or flow basis and the actual sampling interval can be a multiple (up to 12) of the primary interval. The volume of sample obtained can be selected from nine incremental steps up to a maximum of approximately 500 ml. The sampler has a capacity for 28 discrete samples, however, with an available option (a multiplexer), up to four subsamples can be composited into one bottle allowing a maximum of 112 distinct sampling events. A continuous analog stage record was obtained using a Freiz Model AU stage recorder.

Two items were needed to complete the design system: a means of activating the sampler, and a method to record sampling time. The sample activation switch was relatively straightforward. The ISCO sampler will initiate a sampling cycle when two contacts (A and C in Figure 1) in the flow meter connection are momentarily bridged. To accomplish this, four magnets were cemented at equal distances around the 30.5-cm periphery of the stage recorder float wheel and a reed switch was mounted on a sheet metal bracket such that when the float wheel roated, the reed switch opened and closed with the passage of the magnets (Figure 1). Thus, the primary interval for a sampling impulse was a 76-mm (3-in.) stage change. Due to the flexibility of the sampler, many sampling permutations were available. For example, by setting the multiplexer switch on Position 2 and the time interval switch on Position 1, two 76-mm (3-in) subsamples were composited to obtain a sample representing a 152-mm (6-in.) stage change. A second method of obtaining a 152-mm (6-in.) stage change sample would be to set multiplexer on Position 1 and the time interval switch on Position 2. The first method potentially yields more information. The second method avoids composting subsamples from different regimes; i.e., the first subsample from the descending limb of a hydrograph, and the second subsample from a succeeding runoff event.

The second part of this system is an event recorder to indicate the time of the sample collection. An external event recorder might have been used, but this could present problems in relating the sample time to the hydrograph position, especially if the two clocks were not well synchronized. A much simpler and less costly method of recording the time for each sampling impulse is by marking directly on the hydrograph itself. This apparatus consisted of a pulse circuit, a 12-volt coil, and a marking pen. The pen was mounted on the coil so that opening and closing this coil would cause the pen to move. The coil and pulse circuit were mounted on a sheet metal bracket and positioned on the stage recorder so that the pen rested on the hydrograph margin. When the sampler activating switch was closed, a momentary pulse was generated by the pulse circuit, which closed the coil and caused the pen to move. This created a "job mark" on the hydrograph margin. Care should be taken that the pen and coil mounting do not restrict movement of the stage recorder pen carriage at the extreme end of travel. Occasionally, the marking pen would fail to write; however, this difficulty was minimized by monthly replacement of the pen. A copy of the typical record is shown in Figure 2.

The pulse circuit and associated wiring are shown in Figure 3. It is a low drain circuit, suitable for battery operation, and generated only one pulse per switch closing. The system was powered by a 12-volt automotive

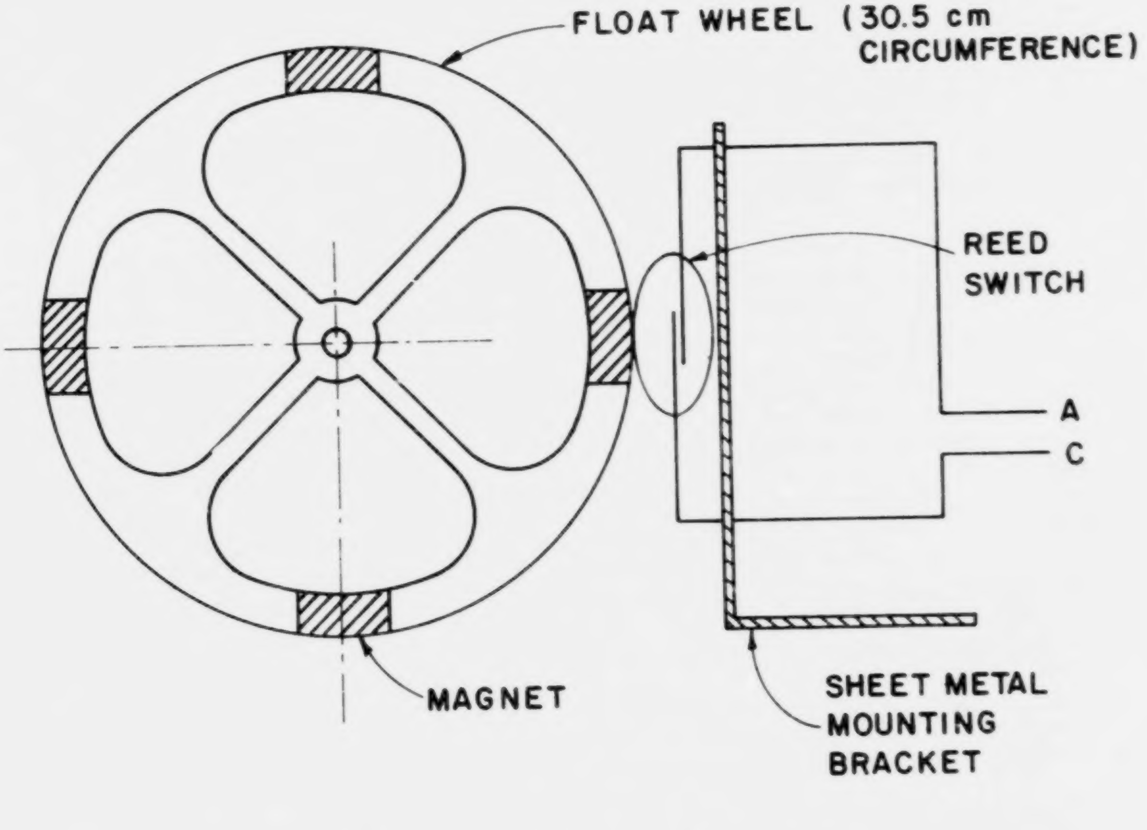
FLOAT WHEEL (30.5 cm CIRCUMFERENCE)
REED SWITCH
A
C
MAGNET
SHEET METAL MOUNTING BRACKET

Figure 1. Sampler activation switch.

storage battery that was recharged once a month. Bench testing demonstrated the proper spacing between the reed switch and magnets necessary so that only one pulse was generated per magnet cycle and that minor fluctuations in stage did not cause multiple sampling impulses to be generated. This varied slightly due to magnet strength but was generally about 6 mm (0.25 in.). To ensure that momentary fluctuations in stage did not cause multiple triggering of the sampler, a 35-μ Farad, 15-volt capacitor was added to the existing circuitry for sample initiation.

Including sample losses in transit and laboratory analyses, less than 10 percent of all possible sampling data were lost over a two-year study period. Thus as a whole, this simple sampling activation and notation package that costs only about $25 has performed very satisfactorily on a continuous field basis. It is well adapted to situations where line power is not available or sophisticated digital recording equipment is not used.

Stage Discharge Relationships--

Stage discharge relations were developed using regression techniques. In three of the four cases, two curves were used. The break point was generally located just above base flow and was visually apparent from a stage

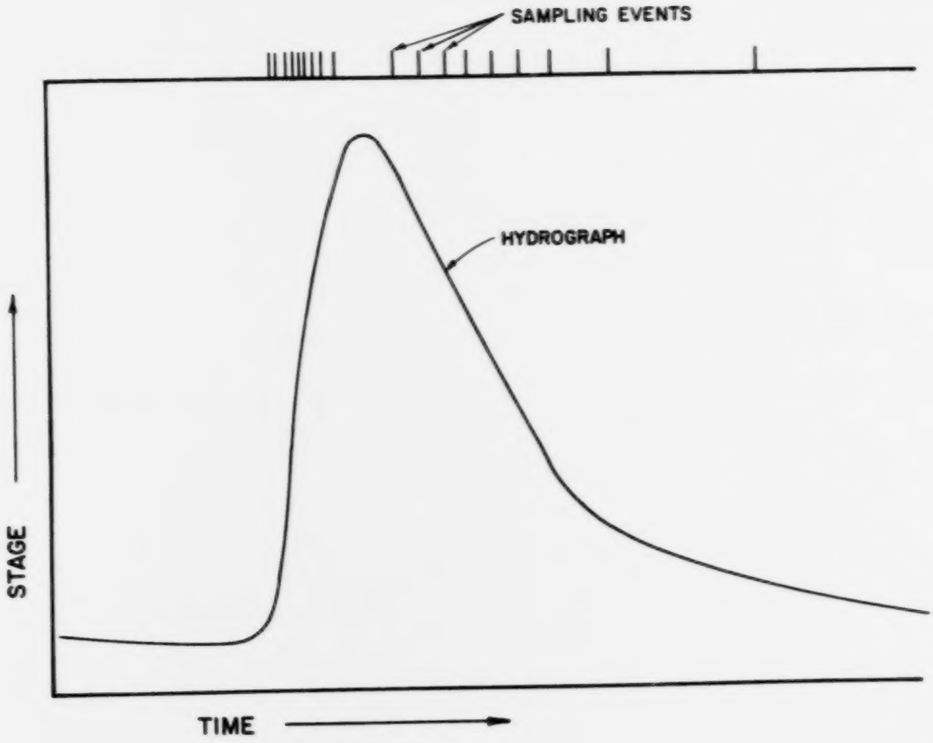

Figure 2. Typical record of a runoff event.

discharge plot. The relation for low flow was a straight line; higher flows were predicted using a second order equation. This provided a better fit than a log-log relation. The high flow relations had r^2 values of .95 to .99 while the low flow r^2 values ranged from .76 to .98. The lesser r^2 values for low flows at two of the sites were judged to result from slight stream bed shifts caused by high flow scouring.

Maintenance--

Maintenance was designed into the initial sampling scheme as it was anticipated that problems would occur if a regular routine was not followed. In addition, the instrument houses were built of heavy gage plate steel rather than aluminum as a protection against damage from firearms since these stations were in highly vunerable rural areas where hunting was taking place. Several bullet marks on two of the station houses proved the wisdom of this

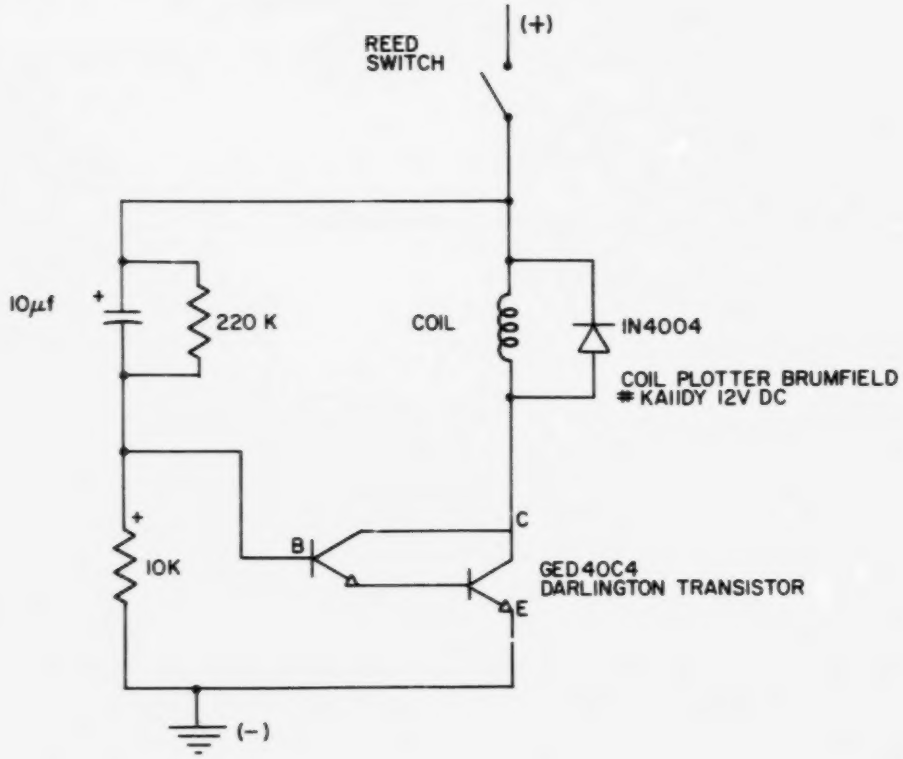
(+)
REED SWITCH
10µf
+
220 K
COIL
IN4004
COIL PLOTTER BRUMFIELD
# KA11DY 12V DC
+
10K
B
C
E
GED40C4
DARLINGTON TRANSISTOR
(-)

Figure 3. Event recorder circuit.

approach. On one occasion the lock securing one of the instrument house doors had been jimmied free resulting in a broken hasp. As a result the recommendation would be made that a hood be built over the lock and hasp to afford added protection.

Record Processing--

Both the rain gages and the stage recorders were analog devices. In order to facilitate analyses and to manage the vast amount of data generated, it was necessary to translate all analog data to computer acceptable digital format. This aspect of the study was very time consuming and highly prone to human error. The rainfall data was manually coded onto computer forms and then keypunched. The stage data was converted to digital paper tape output using an analog to digital converter developed in the Biological and Agricultural Engineering Department at North Carolina State University. Our recommendation would be that future studies of this type employ equipment which would produce computer acceptable format to greatly reduce the error involved and the amount of time necessary for record processing.

LABORATORY EQUIPMENT AND PROCEDURES

Sampling Handling

Sample Preservation--

Sample integrity after collection by either grab or instrumented procedures was a major project concern. Preservation techniques were examined to determine the most feasible procedure for the samples collected in these rural watersheds. Three preservations were used: mercuric chloride, ice, and acid addition to maintain sample $pH<2$. Comparisons were made with replicate samples kept at room temperature.

A single large sample was taken in the field, returned within 15 minutes to the laboratory and split into 12 bottles. Three bottles were preserved with each of the three preservation methods and three were used as control at room temperature (25 °C). Three aliquots of the original sample were analyzed immediately for chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), nitrate plus nitrite (NO_3-N), and chloride (Cl). Then at one week intervals the bottles were sampled and analyzed, Figure 4. There was varying results from week to week for undefined reasons. No clearly superior method emerged from these tests; hence, the preservation was selected for convenience of the analytical tests.

The mercuric chloride method was not used because of interference with the nitrate and chloride analyses. The addition of acid was selected for the instrumented samplers because extended periods could elapse before the sample was returned to the laboratory, and thus ice or refrigeration were not feasible. For the grab samples, storage in ice and then laboratory refrigeration was selected. The use of acid-fixing required considerable time for pH correction prior to analysis and hence was not used on the larger volume of grab samples.

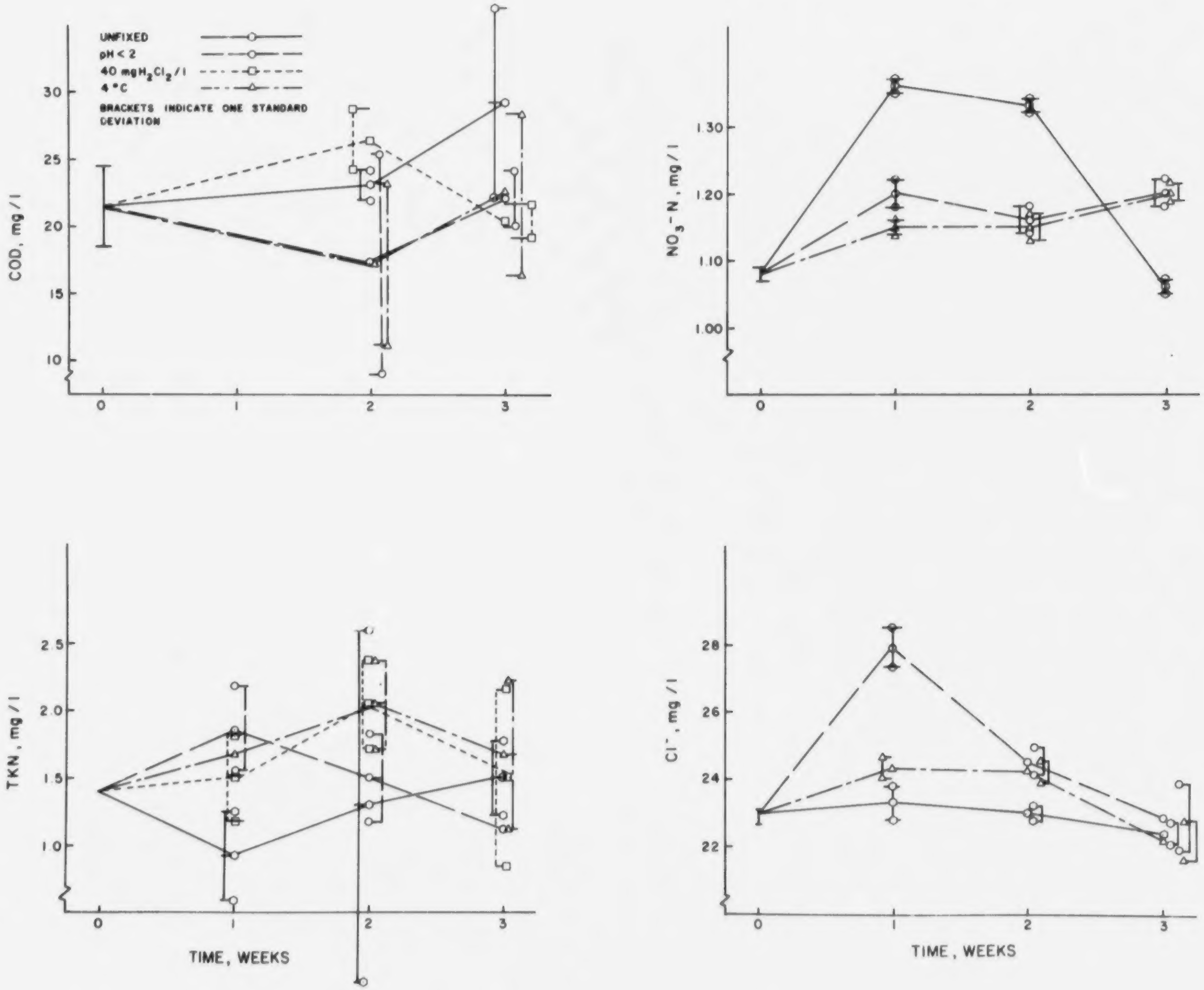

Figure 4. Chemical concentration variation with time for various preservation techniques.

Sample Management

Grab Samples for Chemical Parameters and Sediment--

After collection in the field, the samples were packed in ice and maintained until reaching the laboratory. At that time the plastic bottles were transferred to a 4 °C refrigerator until analyzed.

Instrumented Samples--

When the bottles with acid-fixed samples were taken to the laboratory, each was agitated and transferred to polyethylene storage bottles for refrigeration at 4 °C. Prior to analyses for nitrate plus nitrite nitrogen (NO_3-N) and total organic carbon (TOC), pH was adjusted to a range of 6-8 with a 50 percent solution of sodium hydroxide. Preliminary tests showed no differences in chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN), total phosphate (TP), orthophosphate (OP), chloride (Cl), ammonia (NH_4-N) before and after pH neutralization, so sample pH was not adjusted for these tests.

Distribution of Chemical Analyses--

Every grab sample collected was analyzed for TKN, NO_3-N, TP, and Cl. A probability assignment was made such that approximately 50 percent of the samples were analyzed for COD, TOC, OP, and suspended solids (SS), and 25 percent for NH_4-N.

Instrumented samples were apportioned for analysis such that every sample was tested for TKN, NO_3-N, TP, and Cl; every other sample for COD, TOC, OP, and SS; and every fourth sample for NH_4-N.

Sampling and Analysis--

Complete agitation of refrigerated samples was accomplished with magnetic stirrers. An aliquot was taken for each analysis and the bottle returned to the refrigerator for other analyses. Based on the previously described selection technique, the average percentage of grab and instrumented samples analyzed for respective chemical parameters are given in Table 1. Replicated analyses of samples was not done on a routine basis.

Sample Analyses

The COD was determined according to Standard Methods (APHA, 1971) with the shortened digestion period of 35 minutes verified for these samples (Humenik, 1975; Overcash, 1975). The lower detection limit is about 5 mg/l.

The carbon content of all samples was obtained with a Beckman Model 915 TOC Analyzer. The amount of total carbon was determined by injecting a microsample (20 μl) with a syringe into a 950 °C catalytic (Colbalt-impregnated, asbestos packing) combustion tube. The sample was then vaporized and the carbonaceous material completely oxidized to carbon dioxide and water in the presence of a cobalt catalyst. Zero grade carrier gas transported the generated carbon dioxide to the infrared analyzer for measurement. The carbon dioxide detected was directly proportional to the total carbon of the sample. The actual concentration was determined from the peak recorded on a strip chart, which was compared to a calibration curve.

TABLE 1. LABORATORY-CHEMICAL ANALYSES PERFORMED ON GRAB AND INSTRUMENTED SAMPLES

Percent of total samples collected		
100%	50%	25%
Total Kjeldahl Nitrogen TKN	Chemical Oxygen Demand, COD	Ammonia, NH_4-N
Nitrate + Nitrite NO_3	Total Organic Carbon, TOC	
Total Phosphate, TP	Orthophosphate, OP	
Chloride, Cl	Nonfilterable Residue, SS	

Inorganic carbon was determined by injecting an identical microsample into a 150 °C combustion tube that contained quartz chips wetted with 85 percent phosphoric acid. This temperature was below the value at which organic matter oxidizes. All inorganic carbon was converted to carbon dioxide which was measured by the infrared analyzer. Inorganic carbon values were then determined by comparing the peak recorded on a strip chart to a calibration curve. The sample TOC was then the difference between the total carbon and total inorganic carbon. The inorganic carbon content of the rural runoff samples was in the 1-4 mg/l range.

Analysis of the OP from the start of the project until 4/20/75 was conducted with the stannous chloride procedure (APHA, 1971). The lower level of analytical sensitivity was estimated at 0.01 mg OP/l. With the development of the low level OP automated analysis, all remaining samples were run as an adaption of the Technicon Method (#327-74 W). The determination of phosphorus is based on a colorimetric method in which a blue color is formed by the reaction of OP, molybdate ion and antimony ion followed by reduction with ascorbic acid at an acidic pH (<1). The phosphomolybdenum complex is read at 660 nm.

In order to account for sample color, a separate analysis of background color was made in order to determine the actual sample concentration. From 10/25/75 a dialyser was installed which automatically removed background color. OP concentrations were measured with dialysis and without dialysis (but substracting background level) and found to be the same. With the automated analysis and dialysis procedure, the lower detection limit was estimated to be 0.01 mg OP/l.

Ammonium determinations from project initiation until 10/25/75 were by a manual distillation as described in Standard Methods (APHA, 1971). Utilizing this technique, an estimated lower detection limit of 1 mg NH_4-N/l was achieved. On 10/25/75 the NH_4-N analysis was converted to an adaption of the Technicon method (Number 325-74 W) in which dialysis was used to improve analytical efficiency. The determination of ammonia is based on a colorimetric method in which an emerald green color is formed by the reaction of ammonia, sodium salicylate, sodium nitroprusside, and sodium hypochlorite (chlorine source) in a buffered alkaline medium at a pH of 12.8-13.0. The ammonia-salicylate complex is read at 660 nm. With the automated technique adapted for low level concentrations, the lower level of analysis was estimated to be 0.01 mg NH_4-N/1.

The TKN and TP analysis involved sample digestion to NH_4-N and OP, respectively as specified in Standard Methods (APHA, 1971) with the TKN reagents modified to use 1 g mercuric oxide/1 instead of 2 g/1 of digestion reagents. These reagents have much lower safety risk and cost than the recommended automated digestion reagents (Technicon). From that stage the procedure was the same as described for these parameters.

The block digester (Technicon BD-40) was used with a 20 ml sample and 5 ml of digestion reagent. The digestion sequences were the same as used in Technicon procedures. After digestion and cooling, the tubes were brought to 75 ml volume while being agitated on a vortex mixer. Next each tube was inverted 10 times to assure complete mixing and then poured into sample cups for the automated analyzer.

All TP analyses were by the automated technique with dialyses. However, only the TKN samples collected after 8/31/75 were analyzed in this manner. Prior to that date the Standard Methods (APHA, 1971) technique for TKN was used.

The NO_3-N and Cl analyses were made using adaptions of the Technicon procedures (Number 100-70 W and 99-70 W, respectively). This automated procedure for the determination of nitrate plus nitrite utilized the procedure whereby nitrate is reduced to nitrite by a copper-cadmium reductor column. The nitrite ion then reacts with sulfanilamide under acidic conditions to form diazo compound. This compound then couples with N-1-naphthylethelenedia-mine dihydrochloride to form a reddish purple azo dye measured at 520 nm. The automated procedure for Cl depends on the liberation of thiocyanate ion from mercuric thiocyanate by the formation of unionized but soluble mercuric chloride. In the presence of ferric ion, the liberated thiocyanate forms a highly colored ferric thiocyanate proporational to the original chloride concentration measured at 480 nm. During July to September 1975 these procedures were modified to include dialysis in order to simplify the analyzer operation. This conversion yielded the same results as the undialyzed procedure. With the automated procedure incorporating dialysis, the lower levels of analysis were estimated as 0.01 mg NO_3-N/1 and 0.50 mg Cl/1.

On a number of samples taken from the studied streams, there was an apparent OP to TP ratio in excess of unity. An extensive analysis of the analytical procedures indicated that all standards were determined correctly, and that with known additions of OP and TP, complete recovery of each was achieved. Preliminary tests have identified a possible positive interference with the OP values which did not occur after sample digestion. The nature and magnitude of the interference have not been determined; thus the OP must be viewed with some doubt.

Total nonfilterable residues were analyzed according to the procedures in Standard Methods (APHA, 1971). This determination was made in triplicate and was one of the more variable measurements in this study. The estimated lower detection limit was 0.5 mg/l.

STUDY SYSTEM DEFINITION

Basin Description

The U.S. Army Corp of Engineers, as part of their water resources development studies, made a detailed investigation of the Chowan River Basin. Results of this study were published in a draft feasibility report (Corp of Engineers, 1975). The material in this section is taken directly from that report.

The Chowan River Basin is about 209 km (130 miles) long and drains an area of 12,802 sq. km (4,943 sq. miles) in southeastern Virginia and northeastern North Carolina. The Chowan River proper is located entirely in the state of North Carolina and flows in a southerly and southeasterly direction from the confluence of the Nottaway and Blackwater Rivers at the state line for a distance of 84 km (52 miles) to the entrance of the Albemarle Sound. The three principal tributaries to the Chowan River are the Meherrin, Nottaway, and Blackwater Rivers.

The upper 5180 sq. km (2000 sq. miles) of the basin lie on the Piedmont Plateau in Virginia which is characterized by gently rolling hills. The remaining 7700 sq. km (3000 sq. miles) of the basin lie on the flat Coastal Plain of Virginia and North Carolina. These topographic regions are separated by the fall line running in a general north-south direction roughly through Petersburg, Emporia, and Roanoke Rapids as shown in Figure 5.

The Meherrin River rises in Lunenburg County, Virginia, flows toward the Atlantic Coast in a southeasterly direction crossing the Virginia-North Carolina state line five times, and empties into the Chowan River about 58 km (36 miles) above the Albemarle Sound. The drainage area lies between the Nottaway and Roanoke River Basins. It is about 24-40 km (15-25 miles) wide, about 153 km (95 miles) long, and is comprised of about 4195 sq. km (1620 sq. miles), of which about 2590 sq. km (1000 sq. miles) lie in Virginia and the remainder in North Carolina. The Nottaway River also arises in Lunenburg County. Draining an area of 4403 sq. km (1700 sq. miles) in the center of the Chowan River Basin, it flows southeasterly for 250 km (155 miles) to its confluence with the Blackwater River. While on the Piedmont Plateau, the Nottaway is generally a fast flowing, clear stream. Then, unlike the Meherrin, it also retains its clearness through the Coastal Plain and gradually broadens as it passes through the wooded lands toward its mouth.

The Blackwater river originates on the Coastal Plain just below the city of Petersburg and flows in a southeasterly and southerly direction for 170 km

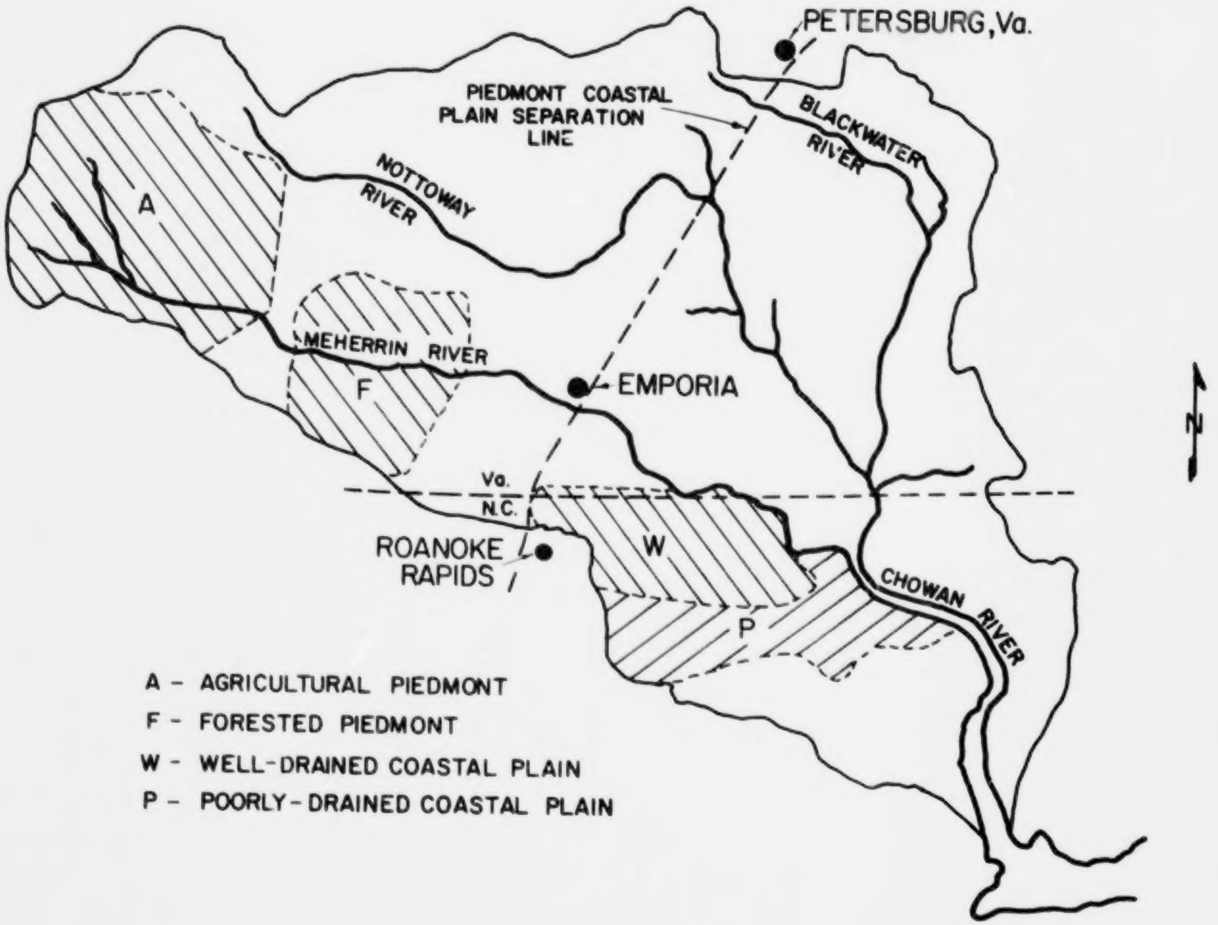
PETERSBURG, Va.
PIEDMONT COASTAL PLAIN SEPARATION LINE
BLACKWATER RIVER
NOTTOWAY RIVER
A
MEHERRIN RIVER
F
EMPORIA
N
Va.
N.C.
ROANOKE RAPIDS
W
P
CHOWAN RIVER
A - AGRICULTURAL PIEDMONT
F - FORESTED PIEDMONT
W - WELL-DRAINED COASTAL PLAIN
P - POORLY-DRAINED COASTAL PLAIN

Figure 5. Schematic of Chowan River Basin.

(105 miles) to its confluence with the Nottaway River to form the Chowan River. This river drains 1920 sq. km (740 sq. miles) of gently sloping and relatively flat terrain on the Coastal Plain of Virginia. It received its name from its color, which is a result of tannic acids the stream receives as it passes through wooded swamplands along its course.

Rainfall over the basin averages about 115 cm (45 in.) per year. The snowfall varies from about 25 cm (10 in.) on the Coastal Plain to 30 cm (12 in.) on the Piedmont Plateau. Runoff from the Chowan River watershed has averaged about 30 cm (12 in.) per year, which is about 27 percent of the rainfall and equivalent to about 0.0098 $m^3/sec/km^3$ (0.9 $ft^3/sec/mi^2$) of the drainage area. The total population of the Chowan River Basin in 1970 was 259,608 of which 66 percent resided in Virginia and 34 percent in North Carolina. The total population for the basin represents a 1 percent decrease from the U.S. census estimate for 1969, or in absolute figures, a decreasing population of 2294. This is primarily the result of a movement of rural agricultural workers and their families to urban areas located outside the basin.

The Chowan River Basin, for the most part, has always had a rural economy. In the 1970's the rural population in the basin was 205,973 or 79 percent of the total population. This compares to 37 percent for Virginia, 55 percent for North Carolina, and 23 percent of the nation. Thus in perspective, the Chowan River is a highly rural basin. However, this is gradually changing as in 1960 the rural population was 89 percent of the total while in 1970 the rural population had dropped to 79 percent of the total. In Virginia the population of the major urban centers in the basin are Franklin, 6800; Emporia, 5300; and Dinwiddy County adjacent to Petersburg, 12,435. In North Carolina, the populations of the major urban centers in the basin are Edenton, 4766; Ahoskie, 5105; and Murfreesboro, 3108. The remainder of the urban population is located in scattered small towns throughout the basin.

Study Area Stratification

There are only two major physiographic regions located in this basin--Coastal Plain and Piedmont. Therefore, two small conveniently located areas (one Piedmont, one Coastal Plain) were arbitrarily selected for study.

Within the Coastal Plain region, previous research (Gambrell *et al.*, 1974) has indicated some differences in water quality parameters in drainage water from poorly-drained soils as compared to moderately, well-drained soils. The poorly-drained soils have a higher content of soil organic matter, and water leaving these soils is higher in TOC. However, saturated, anaerobic conditions within the poorly-drained soils frequently favor denitrification so less nitrate-nitrogen is removed from the poorly-drained soils as compared to well-drained soils. Well-drained soils usually support a more intensive agricultural program and normally have greater slopes as compared to poorly-drained soils. Thus, the sediment losses from well-drained Coastal Plain soils would be expected to be greater.

For these reasons, the area selected for study in the Coastal Plain was stratified for this study into regions where most of the soils are well drained and into regions where most of the soils are poorly drained. The actual subbasins within each of these stratifications were chosen at random but from a restricted portion of the Chowan River Basin; that is, on the North Carolina side of the river within practical working distance of Raleigh.

Within the Piedmont region, there is no simple system for stratification based on soil resources. Nearly all of the soils are Hapludults, and major differences in nonpoint sources of contaminates are likely to be a result of land-use differences. Thus, a random selection of sites was made from within a restricted area to make travel costs reasonable. However, the area chosen was primarily forested; therefore, another Piedmont area with more agricultural activity was then selected to obtain additional sampling sites resulting in the two Piedmont areas--forested and agriculture.

Study Unit Definition

The characteristics of the area sampling plan used were established by two decisions. The first decision was that rural runoff can best be studied as the output of small drainage subbasins that do not have point sources of pollution. The second decision was that small drainage subbasins can best be identified, delineated, and enumerated on some chosen topographic map. The maps used were USGS 1:250,000 maps, AMS series V501 NJ18-10, NJ17-12, NJ17-9, NJ18-7.

A precise but practical definition of a small drainage basin was a basic requirement of this study because of the decision to study rural runoff by measuring constituent concentrations and nutrient transport by random sampling of small watersheds with no point sources.

The first definition of a sampling unit (a small basin) specified sampling a second-order stream below the confluence of the two first-order streams that generated it. The sampling point was to be as far down the stream as possible without receiving the contribution of another tributary. The complexity of this definition resulted from the desire to provide an opportunity to measure stream reach dynamics, as well as nutrient contribution.

Investigators singly or in pairs made several exploratory field visits to each of the randomly selected sites, then all the investigators visited all sites as a team. This exploration of sites proved to be an important step, both in contributing information and in revealing difficulties. In consequence, certain adjustments had to be made in the original plans.

The definition initially set forth in the research plan proved to be impractical at some points in the Coastal Plain, and accordingly was modified. In certain Coastal Plain sites, the confluence of two first-order streams, marked clearly on the map, was difficult to define in the field because of extensive swamp areas, braided channels, and meandering flow. Under these conditions, access was difficult and flow measurement practically impossible on a routine basis. As a necessary accommodation, sampling at these particular sites was transferred downstream to the next road (or rail) crossing. Under these conditions, the original intent to study stream dynamics and determine confluence mass balances could not be realized, though information on concentration and transport variances and costs could be more easily obtained for this feasibility study.

It was also observed on these exploratory trips that small basins formed by the confluence of two first-order streams may vary greatly in drainage area and consequently in the size of the resulting second-order stream. Further it became clear that the distinction between point and nonpoint sources may be difficult to determine. The first-order streams tend to be small at the point where they cross the first road above the confluence and at that point may be highly influenced by human activity concentrated along roads.

The modified definition of a small drainage basin is still based on one selected edition of topographic maps that cover the study area. Now, however, first-order streams are selected and each is traced down to the first road crossing. During this transit, tributaries may be acquired so the order of the stream is no longer constant. The basin is now defined as all drainage above this road crossing. If the resulting basin is considered to be too small, then the next road crossing is designated, assembling in this manner a list of basins of a more uniform area. Selection of a road crossing has the further practical advantage of total stream confinement for field measurement.

Sampling Site Selection

Four sample subbasins were randomly chosen from the poorly-drained and well-drained Coastal Plain, and forested Piedmont; three from the agricultural Piedmont. These same sampling sites were used for the duration of the feasibility study. One selected subbasin was rejected because an impounded lake obscured the upstream confluence point so that the subbasin did not have the configuration required by the original sampling unit definition; the sample site randomly selected next in order was substituted.

The designation and approximate area of the selected sampling sites are shown in Table 2.

Field Sampling Schedule

Field sampling in this study was in two dimensions, space and time. Sampling in space consisted of the selection of field sampling sites; sampling in time produced a sampling schedule according to which the sites are being visited and the measurement made.

Necessary constraints were imposed upon the simple random sampling plan outlined above. First, the study was confined to four subareas (well-drained Coastal Plain, poorly-drained Coastal Plain, forested Piedmont, and agricultural Piedmont) of the Chowan River Basin. These subareas were chosen arbitrarily to reduce travel costs and yet be representative of all major soil types and rural land uses in the total basin. A second constraint was imposed by limiting the number of sample sites and visiting each site on a number of occasions, rather than selecting a site-time sample completely at random from the two-dimensional frame. Third, certain time-space constraints were imposed to reduce travel time as a matter of practical field operations; the sampling sites were associated as work groups to be visited on one field trip, in a

TABLE 2. DESIGNATION AND APPROXIMATE AREA OF SAMPLING SITES

Stratum	Site	Area sq. mi.	Area sq. km
Poorly-Drained Coastal Plain	P-8	4.51	11.7
	P-10	3.74	9.69
	P-11	4.90	11.7
	P-13	38.04	98.52
Well-Drained Coastal Plain	W-3	6.27	16.2
	W-4	0.20	0.52
	W-8	3.31	8.57
	W-10	6.37	16.5
Forested Piedmont	F-1	5.21	13.5
	F-2	6.14	15.9
	F-3	14.06	36.42
	F-7	6.04	15.6
Agricultural Piedmont	A-1	5.57	14.4
	A-4	4.28	11.1
	A-8	1.75	4.53

limited series of sequences, with visits spaced apart in time and with no visits at night. However, weekends and holidays were included in the time sampling frame.

Subbasin Land Use

Because land use is generally accepted to have an effect on water quality, and because many predictive models employ land use as an important variable in generating water quality estimates, it was decided to define both the watershed boundaries and the current land uses within each watershed. Watershed areas were also necessary to calculate areal yields.

The exact boundaries of each of the drainage subbasins in the Coastal Plain used in this study were determined with help from the U.S.D.A. Soil Conservation Service. Topographic maps of the Piedmont sites were used for determination of drainage areas. These boundaries were refined by field checks to resolve uncertainties in surface divides. No attempt was made to determine the pattern of groundwater flow; the assumption was made that ground and surface water divides coincided.

The land-use types selected for characterization were forest (with recently logged areas counted separately), crop, pasture, residential, and water (lakes, ponds). The land use in each drainage area was determined from aerial photographs obtained from the U.S.D.A. Agricultural Conservation and Stabilization Service, dated 1970 and 1971, with information updated and supplemented by on-site visits. Individual land-use areas, as well as total watershed area, were planimetered directly on these revised photographs. The sum of various land-use areas and the total watershed area agreed within one percent in all 15 cases. This land-use information is presented in Table 3.

Sampling Site Descriptions

There were three levels of sampling employed in the study. In each of the 15 subbasins, one station either below the confluence or at the instrumented sampling point was used in the statistical analyses. These stations were designated as "Prime Sites." In addition, three subbasins had sampling points above the confluence to measure constituent conversions and mass balances. Finally, two subbasins were designated for intensive study. This included studies on oxygen demand kinetics and algal populations and growth potential, as well as chemical constituent interconversions. For these two sites six stations, ranging along the stream system, were selected for study.

In addition to the above stations, sampling points to assess main river quality and the relative contribution of point and nonpoint sources in a watershed were established. For the comparison of water quality between the sample subbasins and rivers draining these areas, two stations were selected, one on the Meherrin River below the Piedmont sites and one on the Chowan River below the Coastal Plain sites. For comparison of point and nonpoint sources, six additional stations were selected above and below one of the statistically selected sites to study inputs and interconversions over a stream reach.

Poorly-Drained Coastal Plain (P Sites)--

This entire area is flat, with little or no relief. The cropped areas are extensively ditched to facilitate drainage. Some areas are tile drained to facilitate crop production in these poorly-drained soils. The major crops are corn, soybeans and tobacco with some small grains grown as a winter crop.

SITE P-10 was an intensive site and thus had six stations in the watershed. Station 1 was located on the west tributary about 0.8 km (0.5 mile) above the confluence. The streambed was a channelized ditch 1.2 m (4 ft) wide by 0.6 m (2 ft) deep and was generally dry except during and shortly after rainfall events. Station 2 was on the north tributary and was sampled about 6.1 m (20 ft) above the confluence. This channelized ditch was 2.4 m (8 ft) wide by 1.8 m (1 ft) deep and generally had flowing water. Station 3 was 6.1 m (20 ft) above the confluence on the west tributary and the stream was the same size as Station 2 and was generally flowing. At Station 4, 6.1 m (20 ft) below the confluence, the stream was also 2.4 m (8 ft) by 1.8 m (6 ft) and flowing. Station 6 (Prime Site), an instrumented site, was located about 3.2 km (2 miles) below the confluence. The channel was about 3 m (10 ft) wide by 2.1 m (7 ft) deep and flowed continuously. The bridge pool area was about 12.2 m (4 ft) wide; however, the channel was cut below the pool area and under all but flood conditions flow was within the channel. When the gaging station was installed, a small concrete block control was emplaced; this did not substantially alter the existing flow pattern. Station 29 was 2.4 km (1.5 miles) below Station 6. At this station only chemical, algal, and oxygen demand kinetics samples were taken; no yield measurements were made. This afforded a total stream reach of about 6.4 km (4 miles) for

TABLE 3. LAND USE

Subbasin	Drainage area sq mi	Drainage area sq km	Forest %	Crop %	Pasture %	Developed %	Logged %	Ponds %
Poorly-Drained Coastal Plain								
P-8	4.51	11.68	77.1	17.4	4.2	1.0	0.3	0.0
P-10	3.74	9.69	72.1	25.9	2.0	0.0	0.0	0.0
P-11	4.90	12.69	69.0	23.0	3.0	4.0	1.0	0.0
P-13	38.04	98.52	66.2	26.4	4.7	1.5	1.1	0.0
Well-Drained Coastal Plain								
W-3	6.27	16.24	44.7	53.5	1.3	0.3	0.2	0.0
W-4	0.20	0.52	52.6	46.2	1.2	0.0	0.0	0.0
W-8	3.31	8.57	56.2	41.9	0.4	1.5	0.0	0.0
W-10	6.37	16.50	48.5	43.3	7.0	0.9	0.3	0.0
Forested Piedmont								
F-1	5.21	13.49	72.1	15.0	8.1	0.0	4.8	0.0
F-2	6.14	15.90	91.9	3.7	2.8	0.2	1.4	0.0
F-3	14.06	36.42	90.3	7.0	1.0	0.1	1.6	0.0
F-7	6.04	15.64	82.8	10.6	3.0	2.9	0.7	0.0
Agricultural Piedmont								
A-1	5.57	14.43	63.6	27.0	7.3	0.2	1.7	0.2
A-4	4.28	11.09	55.6	29.9	14.3	0.2	0.0	0.0
A-8	1.75	4.53	38.1	20.6	32.5	1.0	7.6	0.2

algal and oxygen kinetic studies. Station 29 was at a broad sluggish swampy section in contrast to the upstream sites.

SITE P-11 had three stations originally intended to be clustered about the confluence, but field exploration revealed that measurements were not possible in this area because of difficult conditions. Therefore, all three stations were located at flow constrictions. Station 7 was situated on the north tributary about 0.8 km (0.5 mile) upstream of the confluence. The stream was channelized with a ditch 1.8 m (6 ft) by 1.2 m (4 ft) and flowed most of the time. There was a dog pen (20 dogs) located about 30.5 m (100 ft) upstream and 6.1 m (20 ft) from the bank. Runoff from this area during rainfall or cleaning-flushing events had a visible impact on receiving streams. Additionally, there were about 10 houses located along the road crossing the stream and it is suspected that septic tank drainage also entered the stream. A large amount of filamentous algae (predominantly *Anabaena*) could be seen in the pool upstream of the culvert. Station 8 was located on the west tributary, about 0.8 km (0.5 miles) upstream of the confluence and roughly 0.8 km (0.5 mile) south of Station 7. This stream was channelized and was the same size as Station 7. There were about 20 houses along the road and the stream also drained about 1 sq. km (0.4 sq. mile) of urban and developed area in the town of Ahoskie. Station 9 (Prime Site) was roughly 0.8 km (0.5 mile) downstream from the confluence. The sampling point was at a railroad crossing; three, 1.8 m (6 ft) corrugated iron pipes carried the flow under the embankment. There was always flow through one pipe, but the other two carried water only under very high flow conditions. The streambed proper was about 18.3 m (60 ft) wide and had been channelized in the past but was slowly reverting to a natural swampy state with a thin sheet of water about 9.1 m (30 ft) wide slowly coursing through a thick vegetative mat in addition to flow in the 1.2 m (4 ft) by 0.61 m (2 ft) channel.

SITE P-13 was by far the largest watershed in the study with a drainage area of 98 sq. km (38 sq. miles). This site is the Ahoskie Creek watershed which is an active Soil Conservation Service channelization project. There was only Station 10 (Prime Site) on this stream in the main study, but a substudy was done along the course of this watershed. (See below.) Original information from state and local officials indicated that sewage effluent from a small town in the watershed did not drain into the basin. However, analysis of the stream reach study data indicated a high impact upstream of Station 10, and contacts with state regulatory officials (A. C. Turnage, North Carolina Department of Natural Resources and Community Development, Division of Environmental Management, Personal Communication, September 1976), as well as field inspection, revealed that effluent from an 1100-person septic tank was entering the catchment. This is discussed more fully in the section on the stream reach study. At Station 10 the streambed was 18.3-21.3 m (60-70 ft) wide and crossed the road under a 30.5-m (100-ft) wide bridge. There were three additional overflow culverts but these seldom had any flow. This entire area was extensively ditched and channelized.

There were 7 stations in the stream reach substudy, designated AH-1 to AH-7, shown in Figure 6. Station AH-1 was in the headwaters of the stream about 10 km (6 miles) from the origin. The entire catchment was flat and was extensively ditched and channelized. At the sampling point the man-made channel was 9.1 m (30 ft) wide; some sedimentation had occurred and under low flow conditions the channel was 2.5-3 m (8-10 ft) wide and 0.6 m (2 ft) deep. Station AH-2 was Station 10 in the main study, described above. This station was 5.6 km (3.5 miles) downstream of Station AH-1. Station AH-3 was located 8 km (5 miles) below Station AH-2. Again, the entire area draining to this station was ditched and channelized. The stream channel was about 15 m (50 ft) wide and little siltation or revegetation had occurred; thus under all but the lowest flows, the entire channel bottom carried water. Station AH-4 was 5 km (3 miles) downstream from Station AH-3. The channel at this point was 21 m (70 ft) wide and the bottom was relatively smooth and free of vegetation; under baseflow conditions the water was 0.6 m (2 ft) deep. Station AH-5 was on a tributary that drained a large, swampy area to the south of the main stream. This watershed was approximately one-fifth the size of the main watershed. The stream was wide, sluggish, and meandering with a characteristic dark brown coloration of the water. At the sampling point, which was a bridge crossing, the swamp was confined to a channel 15 m (50 ft) wide by 2 m (6 ft) deep. The stream flow was sluggish, with barely detectable velocities. Station AH-6 was located 0.8 km (0.5 mile) downstream of the confluence of the main stream and the swamp. This road crossing was the effective end of the

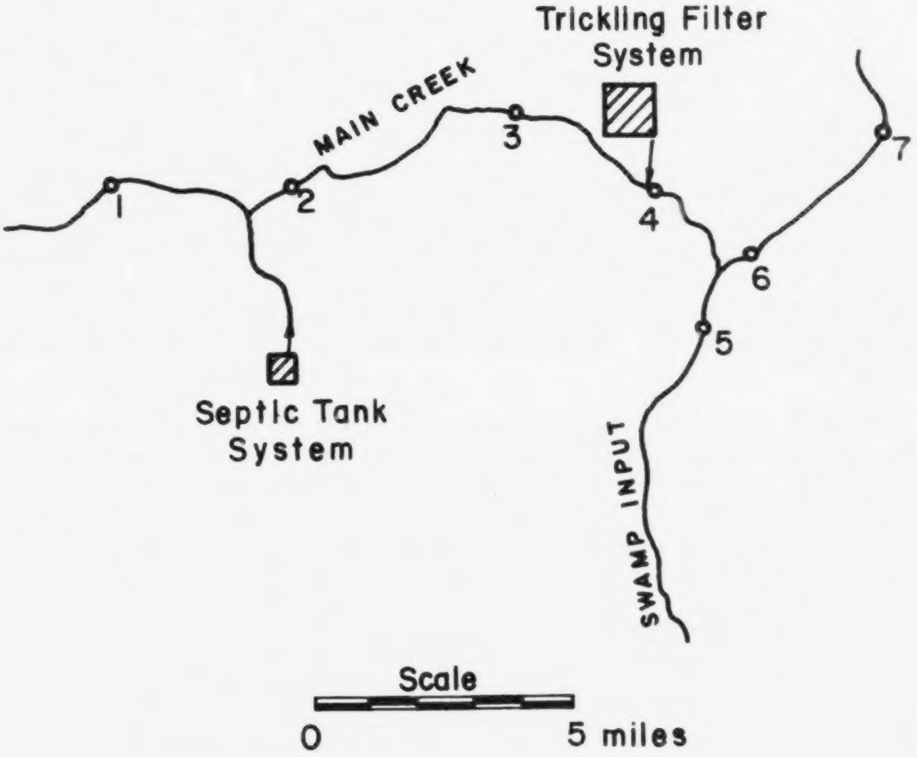

Figure 6. Sampling sites in point and nonpoint source study area.

channelized section of the main stream; below this point the stream was essentially a natural meandering Coastal Plain swamp. At the sampling point the man-made channel was about 24 m (80 ft) wide and 0.9 m (3 ft) deep. This channel was clean and level and generally held water across the entire bottom. The final sampling point, Station AH-7, was 5 km (3 miles) downstream. At this point the stream was broad and flat with a winding channel surrounded by low-lying swampy areas. Velocities were low; under high-flow conditions the adjacent floodplain was under water. The main channel was 21 m (70 ft) wide at the road crossing where samples were taken. The stream was generally less than 1.2 m (4 ft) deep and much vegetation was present in the stream bottom.

SITE P-8 had two stations assigned to the watershed. Station 11 was located at the south tributary, at a road crossing approximately 2.4 km (1.5 miles) from the confluence. The stream was very small at this point, about 0.61 m (2 ft) by 0.3 m (1 ft), and had an extremely small flow except during and after rains when flow increased. Sixty-five houses were located along the road and a roadside ditch fed this tributary. The ditch apparently received input from septic tank drain fields and contained a whitish water with a sudsy scum on the surface. Initial samples exhibited high levels of organics, nitrogen and phosphorus, and a detailed field exploration revealed that a house about 0.4 km (0.25 mile) upstream had a direct, untreated wastewater flow through a pipe into the streambed. Following this discovery, samples were taken above this point; at this location the stream was generally dry. The data summary (Appendix A) includes the early samples with attendant high concentrations, as well as later samples. Station 12 (Prime Site) was located downstream of the confluence at a road crossing. The area above this station was an extensive swamp and the stream was sluggish with a typical dark coloration. The bridge was 15 m (50 ft) wide, the bridge pool was the width of the bridge and about 1.2 m (4 ft) deep at the center. This was also an automated site. The bridge pool never went dry, but during dry periods it was difficult to discern any flow out of the swamp above the station or into the swamp below the road crossing. Frequently, velocities were too low to measure unless the channel was restricted by placing sand bags along the banks.

The main river sampling point, used for comparison to the poorly-drained sites, was designated CHO-1. The sampling point was the U.S. Highway 13 bridge crossing the main stream of the Chowan River. At this point the river is 0.4 km (0.25 mile) wide. The area adjacent to the river on both sides was low-lying and swampy. Under high-flow conditions this area was underwater. The river was sampled from the bridge at the centroid of flow.

Well-Drained Coastal Plain (W Sites)--

In contrast to the poorly-drained area, these watersheds, for the most part, are cropped on the uplands and an extensive buffer zone of woods and swamp extended along stream banks. Three of the four watersheds in this area have extensive swamps representative of the cypress sweet gum biome. Important crops, in addition to corn, soybeans, and tobacco, include peanuts and cotton. While there may be differences in pesticide levels due to the presence of these two crops that are treated with high levels of herbicides, fungicides and insecticides, the level of nutrient application is not greatly different than that for other row crops.

SITE W-3 had Station 13 (Prime Site) located at a road crossing about 9.5 km (0.3 mile) below the confluence. The area above and below the road crossing was swampy; however, a channel had been cut on the downstream side and most measurements were made at this point. A plank walkway across the stream was installed here to facilitate flow measurements under runoff conditions. The bridge pool was wide, deep and always held water; but on a few occasions there was no measurable flow. On one trip during July 1975 this site experienced two days of violent thundershowers which caused a flood that was judged by local observers as roughly a ten-year high.

SITE W-4 had a very well-defined stream channel. The sampling point, Station 14 (Prime Site), was located about 0.3 km (0.2 mi) below the confluence and 0.8 km (0.5 mile) from the nearest road. This was the smallest subbasin studied and was dry on many sampling visits. The channel at the sampling point was about 1.8 m (6 ft) wide and 0.61 m (2 ft) deep. Under high flow conditions the water was out of the banks and spread across the wooded flood plain making flow measurements extremely difficult.

SITE W-8 sampling, Station 15 (Prime Site), was about 0.3 km (0.2 mile) below the confluence at a road crossing. On either side of the bridge the stream was extremely swampy with a braided channel. At the road crossing, the channel was about 15 m (50 ft) by 1.2 m (4 ft) and velocities were so low that current meter measurements were impossible except under high flow conditions. Therefore, a channel restriction was erected, using block and concrete to narrow the channel to 1 m (3 ft) wide and block was laid across the stream bottom to give the best possible measuring section. Under high flow conditions measurements were made from the bridge.

SITE W-10 was almost an exact replica of Site W-8. Sampling Station 16 (Prime Site) was 0.3 km (0.2 mile) below the confluence and was located at a road bridge. The stream opened out into a swamp on both sides of the road. Because the velocities were below detection limits at most times, a channel was built, as Site W-8 except that it was 3 m (10 ft) wide. Site W-10 had a large beaver dam (80-100 ft wide by 3 ft high) on the upstream side of the bridge. Several times during the two-year measurement period the local landowner cut holes in the dam which the beavers quickly repaired. The dam created a two-acre swamp of standing water.

Forested Piedmont (F Sites)--

The area selected is in Virginia and lies west of the fall line and is an intergrading of Coastal Plain and Piedmont in the east to the true Piedmont of the west. The area is predominately forest with small plots of corn, soybeans and small grains present. There is very little tobacco grown in this area. There is very little livestock production in the area, with only a few small swine and pastured beef operations present.

SITE F-2 was selected as a mass balance watershed with three stations. Station 17 was on the northwest branch of the main stream. Access was by logging roads and then a short hike, as the site was approximately 0.3 km (0.5 mile) from the nearest road. The sampling-measurement site was about 6 to 9 m (20 to 30 ft) above the confluence in a well-defined channel about 2.7 m (9 ft) wide by 0.9 m (3 ft) deep. The stream was dry several months of the year and was still measurable by wading during high flows. Station 18 was on the west branch and access was as described for Station 17. The sampling-measuring site was about 6 to 15 m (20 to 50 ft) above the confluence in a well-defined channel about 3.7 m (12 ft) wide by 1.2 m (4 ft) deep. This stream was dry during drought season, but less frequently than at Station 17. During high flow this stream became difficult to measure by wading and there was no bridge for using the Price meter. A wooden plank walkway was laid across the stream and secured with ground anchors, but a flood washed it away between visits. Thereafter, surface flow estimates were made when the stream overflowed its banks.

Station 19 (Prime Site) was 6 to 9 m (20 to 30 ft) below the confluence of the streams with Stations 17 and 18, and access was as for Station 17. This stream ranged from dry during drought periods to a flood stage where it was measured about 183 m (600 ft) downstream at the crossing of the logging road used to gain access. The channel was well defined with rock outcroppings and gravel to sandy banks. At the sample-measurement point the channel was about 4.6 m (15 ft) wide by 1.5 m (5 ft) deep.

SITE F-3 was an intensive site and had six stations in the watershed. Five of these stations were normal measuring sites, the sixth site was sampled for chemical, algal, and kinetic study but flow was not measured. The area was forested and logging had begun in the watershed near the end of the study period. A small amount of farming was noted with corn, soybeans, and home gardening predominating. Also some cattle were being grown on pasture. There were numerous rock outcroppings present in the stream channel, but generally the stream bottom was sandy with stretches of gravel. The stream was typical uplands forest stream and the areas around all six stations were heavily wooded. Station 20 was located on the north branch at a road crossing about 3 km (2 miles) upstream from the confluence of the two tributaries which formed the main creek. Thus Station 20 was the furthest upstream and the channel was small; about 2 m (6 to 8 ft) wide by 1 m (3 ft) deep. Above the road, the creek flowed in a well-defined channel with a broad flood plain through gently rolling hills. Flow measurements were generally taken in this channel. Below the road, there was a large pool about 1 m (3 to 4 ft) deep and 2 m^2 (20 sq. ft) in area. Low flow measurements were taken in a shallow riffle area below the pool. During droughts the stream dried up except for water standing in the pool, and even during high flows the stream stayed within its banks. Stations 22, 23, and 24 were at the confluence of the two major tributaries which formed the main creek, and access was on foot from a logging road 0.8 km (0.5 mile) away. Station 22 was on the north branch about 6 m (20 ft) above the confluence, and the stream channel was well defined and about 3.7 m (12 ft) wide by 1 m (3 ft) deep. Station 23 was on the southeast branch about 15 m (50 ft) above the confluence. Here, a log restriction was put in place to narrow the stream through a sandy area in the channel which had widened at this point to 4 m (15 ft) by 1 m (3 ft) deep. Station 24 was located about 6 m (20 ft) below the confluence. Here, the channel was 6 m (20 ft) wide by 2 m (6 ft) deep. Stations 20, 22, 23, and 24 went completely dry during the drought in the fall of 1976. At times the stream overflowed its banks during flash floods, becoming impossible to wade. Because of the remote location, no alternate high flow measurement points were available, so surface estimates of high flows were made. Station 25 (Prime Site) was an automated, as well as a grab station, and was located on a logging road about 1.6 km (1 mile) off the nearest hard-paved road. This station was approximately 0.8 km (0.5 mile) below the confluence. The bridge was a wooden culvert 4 m (12 ft) wide by 4 m (12 ft) deep. The stream channel above the bridge was well defined and about 3 to 3.6 m (12 to 12 ft) wide by 0.6 m (2 ft) deep. Below the bridge there was a large pool about 1.5 m (4 to 5 ft) deep by 9.3 sq. m (100 sq. ft) in area. A rock dam was constructed below the bridge and above the pool to insure a steady channel around the area of the stilling well. Flow measurements were taken in a fast-flowing, straight, stable section below the pool. The channel here was 1.2 m (4 ft) wide by 0.6 m (2 ft) deep. This stream rarely dried up; high flow measurements were taken with a Price meter off the bridge. Station 28 was a chemical, algal and kinetic sampling point; no flow measurements were taken. The channel was 6.1 m (20 ft) wide by 1.8 m (6 ft) deep.

SITE F-1, Station 26 (Prime Site), was located about 0.8 km (0.5 mile) below the confluence in a wide flood plain on an unpaved, raised roadway with 9.1 m (30 ft) embankments. The bridge was a double culvert with each section being 2.4 m (8 ft) wide by 2.4 m (8 ft) high. Below the road was a large pool about 1.8 m (6 ft) deep and 14 sq. m (150 sq. ft) in area. Flow measurements were taken in a stable section below the pool on the downstream side of the bridge, except that extremely low flow measurements were taken in a sandy area just below the culverts and above the pool. This stream stopped flowing during the drought, but the pool never completely dried up. The stream channel itself was about 3.0 m to 3.7 m (10 to 12 ft) wide by 1 m (3 to 4 ft) deep. High flow measurements were taken with the Price meter from atop the culvert.

SITE F-7, Station 27 (Prime Site), was an automated as well as a grab station. It was located on a paved road about 457 m (500 yd) below the confluence of the two small tributaries which formed the main stream. The roadway here was raised with 9.1 m (30 ft) embankments; and on the upstream side of the road, the flood plain was narrow with steep hills rising sharply on both sides of the creek. Below the road there was a large pool and the flood plain widened considerably. The channel was 7.6 m (25 ft) wide by 1 m (3 ft) deep. Flow measurements were taken about 60 m (200 ft) upstream in an area free of debris because beaver activity resulted in downed trees impeding the flow near the culverts. The bridge was a double culvert 2.4 m (8 ft) wide by 3.7 m (12 ft) high, and the instrument package was attached to a wingwall on the upstream side. During low flows, measurements were taken about 152 m (500 ft) upstream and during high flows measurements were taken from atop the culverts with a Price meter. At the start of this study, the watershed was depopulated of beavers. However, shortly thereafter the subbasin was recolonized. The attendant dam building frustrated efforts to establish a stage-discharge relation; the automated station was subsequently deactivated.

The Meherrin River station, MER-1, was downstream of the F-sites; data from this station was used for comparison purposes. The river was about 120 m (400 ft) wide at this point with a rocky, gravely bottom. It was fast flowing with a pronounced riffle directly upstream of the sampling point.

Agricultural Piedmont (A Sites)--

These selected watersheds were well into the Piedmont and had both forest and agricultural activities. The farms were larger than in the forested Piedmont area with corn, soybeans, and some fire-cured tobacco predominating. Also, there were cattle and some sheep on pasture.

SITE A-8 also had only Station 30 (Prime Site). It was the westernmost site and thus was furthest into the Piedmont. It was located on a paved rural road about 1.6 km (1 mile) above the stream's confluence with the Meherrin River. The stream was a single branch in a well-defined channel about 3.7 m (12 ft) wide by 1 m (3 ft) deep. The stream was slow moving above the bridge, but the section below the bridge had a gravel bottom and about 0.7 (2 ft) of fall over a 6 m (20 ft) reach. Low flow measurements were taken in this section. High flow measurements were taken from the bridge with a Price meter. The flood plain was not wide; rolling hills sloped gently down to the stream.

SITE A-4 had only Station 31 (Prime Site), located on a single reach of stream about 2.4 km (1.5 miles) long above the station. It was located on a state-maintained unpaved road. The channel above and below the road crossing was well defined and about 3.0 m (10 ft) wide by 0.9 m (3 ft) deep. Flow measurements were made under the bridge during normal conditions. Under high flow conditions, measurements were made from the bridge; also, the stream stopped flowing only during very dry weather. The flood plain was fairly typical of the Piedmont area: fairly wide and bounded by gently sloping hills.

SITE A-1 had only Station 32 (Prime Site) which was an automated, as well as a grab, station located at a bridge crossing of a paved rural road. The bridge was about 9 m (30 ft) wide and the stream pooled somewhat under it. The main channel downstream was 4.6 m (15 ft) wide by 2 m (6 ft) deep and the stream was slow moving. Upstream from the bridge the stream was joined by two small tributaries. Flow measurements were taken downstream except during high flow conditions when measurements were taken off the bridge. The instrument package was placed on the bank of the stream on the downstream side of the bridge. Because the stream had a sandy bottom and a meandering channel, a block structure was installed as a control to stabilize the stream and insure that the intake pipes were in the channel.

TECHNOLOGY TRANSFER

To acquaint water quality researchers and planners with the feasibility of using probability ("random") sampling to estimate areawide water quality parameters, three workshops were held in Raleigh, North Carolina; Atlanta, Georgia; and Washington, D.C. The workshop programs were developed in conjunction with the Water Resources Research Institute of the University of North Carolina which along with the North Carolina Agricultural Experiment Station, the North Carolina Agricultural Extension Service, and the U.S. Environmental Protection Protection Agency sponsored these presentations.

Over 150 persons attended these workshops during September and October 1977 and received a 134-page workbook presenting basic principles, project procedures, sample data forms, calculations, and project results. Requests for this workbook were received from many who were not able to attend the workshops. Attendance at the Raleigh workshop was primarily from in-state technical and service agencies whereas a broad spectrum of national representatives attended the Atlanta and Washington sessions.

These workshops allowed immediate dissemination of project results on the feasibility of statistical sampling. Further, the extensive data collected during this feasibility study provided base for making water quality judgments and assessing ongoing or proposed water quality programs.

The topics covered the first day of a workshop were project scope; probability sampling; drawing up a sampling plan: work session; field and laboratory procedures and problems. Topics presented on the second day included statistical results: estimates, precision and cost; substantive results: conclusions, recommendations and discussion. An extended time was set aside for discussion and questions following the presentations.

The need for these workshops and their nature is described in the advance notice:

> Workers in water quality have seen an explosion in the scope of their responsibilities in recent years. Nonpoint sources and the 208 planning and implementation process have become of primary concern because traditional technology is not suitable to point source contributions on an areawide basis, the total number of sites (hundreds) is too large for complete coverage, and therefore some method of sampling must be used. Similar sampling needs arise in evaluating urban runoff, air pollution impact and initial assessment of possible pollutant or hazardous material problems in agriculture and forestry.
>
> This workshop is based on a three-year study of the feasibility of using probability ("random") sampling in measuring rural runoff, carried out by an interdisciplinary team at North Carolina State University. Members of this group will present the statistical, chemical, and operational methods they have developed and will discuss how the results can be applied by others.
>
> This sampling technology is just now being applied to the water quality area. This approach allows sampling with various budget levels, precision estimates, and assesment of problems on an areawide basis. This workshop will demonstrate the effectiveness of this sampling tool and its transferability to other problems and areas.

We continue to receive inquiries about the potential of statistical sampling for evaluation of nonpoint sources and areawide water quality because of these workshops and results presented through other professional contacts and publications. In fact, watershed sampling following the rainfall proability sampling plan developed in the initial portion of this project was initiated in May 1978 by the North Carolina Department of Natural Resources and Community Development, Division of Environmental Management, in conjunction with the agricultural portion of the North Carolina 208 program. This field testing of sampling stratification on the basis of rainfall probability is being executed by this state regulatory agency under supervision of University faculty involved in this EPA grant. This opportunity to work with a state regulatory agency in testing the feasibility of statistical sampling provides mutual benefits and allows a realistic test of a service agency's ability to conduct this type of field monitoring. It also demonstrates that the rainfall probability concept developed during this project is acceptable to a state water quality agency and can be implemented when circumstances suggest that it may be the most cost-effective sampling strategy.

The User Manual being developed to demonstrate the actual utilization of the developed methodology to statistically assess areawide inputs from rural, urban, municipal and industrial sources throughout an actual watershed represents an additional technology transfer opportunity associated with this research project.

SECTION 4

STATISTICAL PROCEDURES AND RESULTS

by

Don W. Hayne

INTRODUCTION

Recent demand for information on the quality of the waters of the nation has presented workers with an unprecedented problem of coverage. This study explores the feasibility of using probability sampling to derive estimates of average water quality in a river basin and in particular to study the small headwater drainages to which the primary contribution is rural runoff.

Determining water quality in all small drainage subbasins of a river system is one of many problems where it is impossible to achieve complete and continuous recording. Were such complete recording possible, it would, of course, be superior to any system of sampling. Consideration of sampling is enforced here, and elsewhere, by the impossibility of complete coverage; for this same reason, sampling is a pervasive element of our scientific, commercial and personal life.

There are two broad objectives of any sampling study. First, it must provide the right kind of information, and second, it must provide information of the best quality possible under the budget. Often the first time a clear definition of exact objectives is required is in planning a sampling study when decisions must be made about exactly what to measure and how. As to the second objective, quality is defined in terms of accuracy and precision, two terms of different meaning. Accuracy has to do with the reduction or elimination of bias, while precision describes the repeatability of a measurement or an estimate.

Both accuracy and precision may be improved through survey design. Accuracy is attained by using probability (or random) sampling; precision is increased by changing sample size and by use of a survey design which is adapted to the universe under study and which allows the available sampling effort to be employed with the greatest efficiency.

A unique feature of sampling the small subbasins of a river basin is that it must be in two dimensions, in space among subbasins, and in time throughout the year. The larger the number of subbasins sampled, the less frequently each may be visited under any constant budget.

In the present study we made a probability sampling study of water quality of small drainage subbasins in a portion of the Chowan River basin of North Carolina and Virginia, gathered data for two years, carried out an analysis of costs and variance components, and based on these findings, made estimates of the precision attainable under optimal allocation of sampling effort for a range of possible budgets. Using the same information and methods, we made comparisons of the cost-effectiveness of grab sampling (use of hand methods at field sites) compared with automated (instrumented) sampling.

CONCLUSIONS

Conclusions of this study must be drawn within the constraints of our basic assumptions: that we are to determine water quality for the output of small drainage subbasins as river-basin averages of such quantities as concentrations of chemical parameters, or rates of flow, or transport or yield of water or chemicals; that reference is to a one-year study; and that the basic objective is the most precise information for the available budget. In these terms, these conclusions follow from our study of a portion of the Chowan River basin.

When identified as the output of small drainage subbasins, rural runoff can be measured by use of probability sampling in space and time. Concentrations were measurable with good precision. Flow, and other measures such as transport or yield of chemicals, which included the flow as a component, were not measurable with good precision, although adjusting flow or transport to yield by taking account of basin area improved precision somewhat. These conclusions hold whether grab sampling or automated is to be used.

Precision was difficult to attain for flow or related measures for two reasons. First, there was high inherent variability, both in space among small drainage subbasins, and in time at any site. Second, and this is true also of measuring concentrations, sampling was required in two dimensions, and because both the space and time components of variance were important, neither was reduced in direct proportion to increased total sampling effort. Rather, each, and their sum, was reduced in rough proportion to the square root of the total sampling effort. Thus, for flow, not only was the variability inherently high, but precision responded slowly to increased sampling effort. For concentrations, the variability was not so high and better general precision could be attained, even though the same requirement for two-dimensional sampling existed as an impediment when attempting to increase precision. These problems concerning variability exist by the nature of sampling river basins; they do not arise because probability rather than judgement sampling is used.

We found that grab sampling promised better precision than automated sampling for the same cost at modest budgets. Grab sampling is more flexible and adjusts easily to the need for more sampling in space. In comparison, automated sampling is costly for sampling in space but provides low-cost sampling in time at any site where installed. Speculation suggested that automated sampling would generally become more cost-effective than grab sampling at high budgets (several hundred thousand 1975 dollars or higher).

We found stratification in time generally worth the effort in terms of increased precision, but it is possible to over-stratify and reduce efficiency by planning too-frequent visits to too-few sites.

Optimal allocation of sampling effort is important to efficiency and may be calculated, given information on costs and variances. We found, however, that optimal allocation differs with the parameter. Because a survey can rarely be planned for a single parameter, this means that the sampling effort must be allocated to be of median efficiency on the average, but probably near optimal for only a few parameters. Based on our experience, such a compromise design might have the number of sites sampled approximately equal the number of visits per year to each site, although this entirely empirical suggestion must be reexamined when more information is available.

RECOMMENDATIONS

Probability sampling in space and time should be employed when determining river basin average values, in particular, averages of the contribution of small headwater subbasins to a river system.

For short-term (ca. one year) studies under modest budgets (less than 100,000 1975 dollars) the use of grab-sampling methods should be given serious consideration on the basis of cost-effectiveness. The longer and more costly the study, the more the balance shifts toward favoring automated sampling, especially in studies of flow, transport, and yield.

A purely empirical suggestion, based upon current information, is that in such a one-year study based on grab sampling, the sample number of sites should be approximately equal to the number of annual visits made to each site. This rule-of-thumb must be reexamined with a broader data base.

Time strata should be delineated in such a one-year survey design after the number of visits has been determined, with two visits per time stratum. Relatively good precision may be expected of sampling studies of concentrations.

THE USE OF SAMPLING

Why should sampling be used; why not study the whole universe of interest instead of only a part? The primary reason is that even if the whole universe could in principle be studied, it usually costs too much to do so. Even if the whole universe could be studied, it often happens that only a superficial examination could be made, with study in greater depth possible only for a sample. Sometimes complete study is impossible because measurements are destructive; chemical and biological samples must often be destroyed to be identified. In choice of sampling method, most factors relate to the balance between cost and precision.

A sampling study must be possible to carry out. Further, it should be reproducible and yield unbiased results, or if results are biased, then there should be an understanding of the bias. Finally, a sampling study should provide some measure of precision of the estimate to guide the user of the information.

Use of Probability Sampling

Why use probability sampling? Up to this point, discussion of sampling has been general without specification of whether the sample was random or one selected by judgement. The most-frequently asked question is how a random number table or coin toss can be instrumental in selecting a better sample than one derived through the judgement of an experienced investigator. The answer rests upon the definition of better and this reflects the advantages of probability sampling.

Probability sampling has several advantages. First, it prevents bias from the unconscious action of personal selection. Studies in several areas have shown that when samples are selected by judgement they tend to be biased in that they reflect the investigator's personal views of the distribution of values for items in the universe. Although the mean value for some fraction of the possible random samples may lie farther from the mean of the universe than any judgement sample, the probability sample has the advantage of being ultimately objective and providing assurance against personal bias in selection.

A second advantage of probability sampling is that it allows use of statistical methods for making tests and inferences. These statistical methods are based upon mathematical reasoning which assumes random sampling and random events. Judgement sampling depends upon human behavior which is infinitely variable and subject to the required mathematical analysis only under very restrictive assumptions about its nature. For the purpose of being able to use the large body of work in mathematical statistics that supports the battery of applied methods, the assumption is often made that judgement sampling is effectively random. Yet when this assumption is tested empirically, it is usually found to be in error.

A third advantage of probability sampling is that the work is absolutely repeatable as to method. One worker can follow the same sampling method at another time and place just as well as the original investigator could. In contrast, a judgement sample is doubtful of comparable repetition even by the same worker at another time or place and impossible of repetition by anyone else because it is based upon a subtle combination of quantitative information, hunch, and a subjective distillation of experience.

Probability sampling methods are widely known to be objective and to negate the potential criticism of subjectivity of choice of illustrative examples. At the same time, to simply state that samples are taken randomly is no guarantee of objectivity; acceptance of any scientific knowledge must rest upon faith in the integrity of the investigator.

Stratified Random Sampling

Any probability sampling design should be planned to take maximum advantage of professional judgement and experience in setting up the sampling design. The difference is that judgement is taken account of in the form of the design, rather than in the ultimate selection of the sample from the universe. There are several methods of accomplishing this purpose; the only one to be discussed here is stratified random sampling. Here the universe is divided into parts which in principle include the whole universe and are non-overlapping. Each of these parts is then studied separately, often with a different sampling intensity. The primary statistical objective in dividing the universe into parts is to create units within which the variability is less than in the whole. For example, if the flow of water is known to be strongly seasonal in pattern, it is only good sense to make separate studies of the different seasons and sum the results for an annual total rather than ignore seasons. Stratified random sampling also allows the allocation of increased sampling effort to the more important parts of the universe. Other advantages are that it allows separate estimates to be made for the separate parts of the universe, subject to the fact that only part of the total sample is available for this purpose. Stratified random sampling may also be used simply to assure that there is a relatively even distribution of sampling effort over all parts of the universe.

Stratified random sampling is discussed in numerous works on sampling techniques. A good exposition at the user level is Chapter 17 in Snedecor and Cochran (1967) while more technical discussions will be found in Cochran (1977), Yates (1960) and Hald (1952). Although the mathematical background is presented by Riggs (1967), Chow (1964) and Haan (1977), none of these references deals with stratified random sampling.

Design of Present Study

The sampling design of the present study reflects the physical nature of a river basin and its component small drainages. There are many small drainages, of which only a sample may be selected for study. These drainages are changing in time and may be measured only at sample instants in time. Time is divided into periods or strata, within each of which two sample times are selected. Thus we are sampling in two dimensions, space and time. Ideally, we should sample at random in the space-time matrix, but this is physically impossible; we must select certain sites, and visit all of these within some short interval, chosen at random from the available time. It is not practical to select a new sample of sites at each visit; a certain amount of exploration and site preparation is required even for grab sampling, and automated sampling requires established sites.

STATISTICAL MODEL AND OPTIMAL ALLOCATION

In this study we are sampling in two dimensions, space and time. Measurements are made at a number of small drainage basins, randomly selected from a complete listing of such basins, and at each of these selected sample drainages, measurements are made at times selected in a restricted random fashion within time periods. These periods constitute a stratification in time, and were set at 4 weeks in length for this study, with 13 periods per year. Throughout the following discussion of the statistical model, the figure of 13 periods per year is treated as a constant; the discussion, however, is more general and applies to periods of any length. In fact, the empirical results suggest that we should have used longer periods. The element of stratification in space is not considered in this discussion of the statistical model. The model applies independently within strata in space, without considering the problem of allocation of sampling effort among strata.

An additive linear model is assumed in the following discussion, but in fact, because the data were log-transformed for analysis, the model is actually multiplicative and variances assumed to be proportional rather than absolute.

The Statistical Model

The problem, then, is of sites randomly selected in space, and visited at randomly selected times within each successive time period. Under these conditions each measurement is assumed to conform to the following linear model:

$$X_{ijk(j)} = \mu + S_i + \Pi_j + (S\Pi)_{ij} + V_{k(j)} + e_{ijk(j)} \tag{1}$$

where $X_{ijk(j)}$ = the single measurement made at the i^{th} site in the j^{th} period and the k^{th} visit within the j^{th} period

μ = general mean

S_i = effect of i^{th} site (random)

Π_j = effect of j^{th} period (fixed)

$(S\Pi)_{ij}$ = effect of interaction, i^{th} site and j^{th} period (random)

$V_{k(j)}$ = effect of k^{th} visit within j^{th} period; this also includes any possible batch effect in chemical analysis (random)

$e_{ijk(j)}$ = random measurement error, which includes any interaction of site with visit within period, the variability due to field sampling, and that due to variance of chemical analysis within batch, or to other sources of random error.

The variance of this single observation will be:

$$\text{var } X_{ijk(j)} = \sigma^2_S + \sigma^2_{(S\Pi)} + \sigma^2_V + \sigma^2_e$$

where σ^2_S = variance due to differences among sites

$\sigma_{(S\Pi)^2}$ = variance due to site x period interactions

$\sigma_V{}^2$ = variance due to differences among visits within sites

$\sigma_e{}^2$ = variance due to random error.

This variance is considered within time strata (periods) and therefore the variance among periods drops out as a result of stratification in time. The number of periods to be used is a constant element, set before the number of sites and visits is decided.

The variance of the mean value for s sites each sampled at pv visits, is:

$$\text{var } \bar{x} = (\sigma^2_S/s) + (\sigma^2_{(S\Pi)}/sp) + (\sigma^2_V/pv) + (\sigma^2_e/spv) \qquad (2)$$

where elements are as described previously and:

s = number of sites

p = number of periods

v = number of visits per period.

This variance must be synthesized by estimating variance components (σ's) from the field data and substituting in the relationship, using the denominator values actually used.

When estimating variance components from field data a small negative value may sometimes occur. In such case, the component was assumed to equal zero because a variance, being a squared quantity, cannot carry a negative sign. In the case where the component $\sigma^2_{(S\Pi)}$ had a negative value (and was assumed to be zero) the components were recalculated, dropping the element $(S\Pi)_{ij}$ in formula (1), and using the following model for the variance of the mean:

$$\text{var } \bar{x} = (\sigma^2_S/s) + (\sigma^2_V/pv) + (\sigma^2_e/spv). \qquad (3)$$

The variance components used for automated sampling were those derived from grab-sampling data (because of the very small number of samplers used). The estimation of flow and of water yield through use of automated sampling sites was a special case of formula (2), in that the components for visits and for periods were absent because measurement of flow was essentially continuous. Only components for sites and measurement error remained. Because we lacked an estimate of measurement error, it was assumed to be zero, and the variance of the mean to be:

$$\text{var } \bar{x} = \sigma^2_S/s$$

thus probably underestimating the variance and favoring automated sampling in comparison to grab sampling. Where concentration was assumed to be measured by automated samplers, the full statement of formula (2) was used as though water samples were to be taken at random in time.

To use the model to calculate a standard error of a mean, values of variance components must be substituted in formula (2) along with the denominator values based upon the sample sizes used, and the variance calculated. The complexity of the model makes this approach necessary. The square root of the variance is the standard error. The variance (and standard error) as usually calculated from the mass of data without taking account of the relative contributions of the different components can provide, at best, only a rough measure of general variability, and cannot be used to appraise the precision of the estimate.

To increase the precision of an estimated mean value, one must reduce its standard error. The components of variance in formula (2) are estimates of system parameters and are not subject to directional change with more or less sampling (although they may fluctuate randomly by sampling error). Therefore the only way to reduce the variance of the mean (with the same sampling design) is to increase sampling effort, thus increasing the denominator values.

Inspection of formula (2) shows, however, that increasing the number of sites sampled will decrease some of the terms while increasing the number of visits will decrease others. Under a constant budget, an increase in number of sites will require a reduction in the number of visits that may be made to each site. The problem of optimal allocation is to find the combination of number of sites and number of visits that will minimize the variance of the mean under a constant budget.

Optimal Allocation

Optimal allocation (sometimes called Neyman allocation) here follows closely the classical method of J. Neyman (as expounded in numerous references, e.g., Cochran 1977). First, a cost function is set up as:

$$C = s(c_s + pvc_v)$$

where C = total available budget (not including the fixed costs of the survey)

c_s = cost of establishing a site exclusive of cost of visiting and sampling

c_v = average cost of visiting and sampling an already established site.

Then:

$$s = C/(c_s + pvc_v) \qquad (4)$$

If formula (2) for the variance of the mean is rewritten in these terms, then:

$$\text{var } \bar{x} = (\sigma_S^2(c_s + pvc_v)/C) + (\sigma^2_{(S\Pi)}(c_s + pvc_v)/pC) + (\sigma_V^2/pv)$$

$$+ (\sigma_e^2(c_s + pvc_v)/pvC.$$

Next, take the derivative of var $\bar{x}$ with respect to v, equate to zero and solve for v:

$$v = [(C\sigma_V^2 + c_s\sigma_e^2)/pc_v(p\sigma_S^2 + \sigma^2_{(S\Pi)})]^{\frac{1}{2}} \qquad (5)$$

The solution for v gives the optimum number of visits per period, that is, the number that will produce the minimum variance. This value must be rounded to an integer: with the present survey design, there must be 2 or more visits per period to provide an estimate of variance within each time stratum.

Given a value for v, the number of visits per period, the available budget determines the number of sites that can be covered, according to formula (4). This value of s, the number of sites, must also be rounded to an integer. This practical requirement for integral values of both visits and sites prevents a precise matching of available budget and estimated cost.

This solution differs from the classical result with hierarchal sampling where the optimal number of the secondary sampling unit depends only on the variances and costs of the primary and secondary sampling units, and not on the budget. In the present case there is no distinction of primary and secondary units even though there is a superficial resemblance in that sites are established and then visited repeatedly. The solution here requires a knowledge of the budget.

Once the optimal numbers of sites and visits are calculated for a given budget and set of variance components, the best precision attainable can be estimated, using formula (2). This device is used later to explore the potential precision when using either grab or automated sampling, and to compare the possibilities of the two methods in a standardized manner.

COST ANALYSIS

Information on cost is basic to planning any investigation. Cost-efficiency is the primary argument for use of sampling of any type, be it probability sampling or judgement sampling; if there were no cost considerations every parameter would be studied continuously and at every point. But in fact, the availability of information is always limited by the cost of obtaining it and some kind of cost analysis is made before undertaking any investigation.

Cost is especially important in the type of investigation described here and in considering the optimal allocation of sampling effort among sites and visits. Not only must the relative cost of establishing a site in comparison to the cost of a visit to an established site be known with fairly good precision, but it is important that these costs be accurate in relation to the total budget. For this reason, we undertook as complete an analysis of the costs of probability sampling as was within our capability. On the other hand, there is no doubt that we would have benefited from the help of a professional in this area.

Because dollar costs of goods and services rose during the course of our study, and have risen considerably since it ended, we have stated all costs in 1975 dollars. Thus we reduced some costs to prices paid during that calendar year for inclusion in our analysis. Anyone attempting to use our cost information for general guidance must use some economic index to inflate our costs to current levels.

To make this cost analysis, we found it necessary to define the kind of investigation as a standard of reference. We assumed the objective to be for an agency report based upon a study of one-year duration and with no research aspects. This qualification meant that we could not transfer the costs of our investigation directly to our analysis because we had carried on numerous larger or smaller research studies, and because our investigation was to explore feasibility and not designed to report on the basin-wide status of water quality. This postulated one-year study would cover a river basin similar to the Chowan River and would determine average flow, yield of water per unit area of drainage basin, concentration of chemicals and transport and yield of chemicals. Algal studies were not included in the cost analysis.

Cost Function

In making the analysis of costs, we broke each down into either a fixed cost, a per-site cost, or a per-visit cost, in conformity with the following cost function:

$$\text{Total Cost} = c_1 + sc_s + spvc_v$$

where c_1 = constant cost

c_s = per-site cost (proportional to number of sites)

c_v = per-visit cost (proportional to total number of visits to sites)

s = number of sites

pv = number of visits per site (product of number of periods and number of visits per period).

In this relationship, constant costs are the same regardless of the magnitude of the study and constitute the overhead required to undertake a study, no matter how small. The per-site costs are the share of the single site in those costs that are proportional to the number of sites. This is the cost of adding another site no matter how many or few visits are to be made and includes the planning, exploration and location of the site, site preparation and instrumentation if any, or construction if it is an automated site. Costs of the minimum number of service trips required to operate an automated sampler should be listed as per-site costs. Per-visit costs include a pro-rata share of all costs that are proportional to volume of day-to-day operations, such as travel, subsistence, supplies, laboratory analyses, data management and physical and administrative costs that are proportional to volume.

Basis of Cost Estimation

The activity to carry out the study was assumed to be ready to function, staffed with knowledgeable investigators who would be available at any level of employment, thus avoiding the problem of planning a study to fit full employment of personnel. The availability of basic facilities and services was assumed, with this cost being covered by overhead charges which we calculated as 50 percent of personnel costs. Appropriate motor-pool vehicles were assumed available at a charge of $0.15 per mile and field subsistence was calculated as $23.00 per day. Our own field costs per sample were doubled to allow for covering an entire river basin rather than only the conveniently located study areas which we used to minimize travel. We assumed that there would be no added costs for taking more water samples after the first one was taken by the team when it reached a site on a particular trip.

Personnel were assumed to be available, trained in the required skills, and employable by the hour at any fractional level up to full time. The costs of accomplishing tasks were mostly counted in hours and then evaluated on the basis of a work year being 2,080 hours with annual reimbursement of personnel (including fringe benefits) being set at:

Administrator	$25,000
Investigator	$16,000
Trained technician	$ 9,000.

All equipment was assumed to be totally depreciated at the end of a one-year study.

For field construction at sites to have an automated sampler and recording gage, the work was assumed to be contracted but with planning, supervision, and inspection remaining a cost to the investigating agency. This field construction would cover a stilling well and a vandal-proof instrument housing. Use of a digitalized recording gage was assumed. To calculate the costs of automated sampling it was necessary to make assumptions about the number of service visits and the number of water samples to be taken and stored between these visits. The figures of weekly visits and 3.3 samples per visit were used, drawn from our experience with a stage-activated system.

The per-site and per-visit costs for using an automated sampler were calculated two ways (which yielded the same overall cost of an automated site). In the first calculation, the cost of weekly service visits was allowed as a per-visit cost, to which was added the cost of chemical and statistical analysis of the average 3.3 samples taken per week. The second method of calculation reasoned that weekly service trips to the sampler were an absolute requirement of any use of the instrument, and therefore that the cost of 52 service trips should be added to the annual per-site cost. This view reduced the per-visit costs to those of chemical and statistical analyses of a single water sample. This second method of calculation is necessary if one is to speculate on the optimal allocation of automated sampling resources between number of sites and number of samples per site.

The costs of chemical analyses were assumed to be contracted to a commercial laboratory with the costs of supervision, record keeping, and quality control remaining as further costs to the project. To establish the costs of the chemical analyses we obtained from several commercial laboratories their charges for handling a range of water analyses at several levels between 250 and 3,000 per year. The resulting information showed general use of a volume discount with the costs fitting fairly well the following linear function:

total cost = \$2,200 + \$30.10 (number of analyses).

This function fitted well only if more than 250 analyses were planned and yielded results that were somewhat high for 3,000 analyses. It did, however, provide us with information in the form of our cost function. The planned determinations included in each analysis of a water sample included: chemical oxygen demand, Kjeldahl nitrogen, nitrate, total phosphorus and chloride for every sample; biological oxygen demand (5-day), total solids, and ammonia for one-quarter of the samples.

For data management, we assumed that general facilities would be available, including a high-capacity computer, general software, and competent personnel, for the use of which standard computer charges would be paid. We estimated the cost of developing our specific software such as programs, procedures and storage and have listed this as a separate item. We have attempted to estimate the reduction in costs if some other agency were to use our computer programs instead of developing their own; such use of our work would have to be based upon familiarity with SAS (Barr et al. 1976).

METHODS OF PROCEDURE

The primary objective of this study was to explore the feasibility of applying probability sampling to the characterization of rural run-off as represented by the output of small drainage basins. A secondary objective was to compare the cost-effectiveness of grab sampling and automated sampling in making this characterization. To accomplish these objectives we went through all the steps of a probability sampling survey with the only departure from a real survey being that we restricted our activities to a relatively small portion of the Chowan River basin. By not covering the entire basin we were able to devote more of our resources to field sampling and less to travel.

Any sampling survey proceeds according to six steps. First, there is defining the problem, then second, building a sampling frame, third, selecting a sample, fourth, gathering the data, fifth, making an estimate of some characteristics of the universe under study, and sixth, describing the precision of the estimate by calculating a variance or standard error.

Definition of the Problem

Definition of the problem includes a statement of its general form, and identification of the appropriate statistical model (as outlined previously). It also includes a precise statement of the universe under study, and a delineation of what parts of the universe are to be excluded from study.

Sampling in this problem was in two dimensions, spatial in the selection of sites for study, and temporal in the selection of times to visit these sites, with time stratified into 4-week periods. The decision to use 4-week periods was made arbitrarily at the start, based upon the need to have two visits to each site within each period (to provide a basis for calculating a variance), and the number of sites thought practical to cover. In the actual study, there was also an element of stratification in space in that 4 study areas were arbitrarily chosen as easily accessible work sites, each represented a recognizable geoclimatic type. Within each of these study areas all sites were listed and a total of 15 chosen at random, with 4 sites in the well-drained coastal plain, 4 sites in the poorly-drained coastal plain, 4 sites in the silvicultural piedmont and 3 sites in the agricultural piedmont. This selection of different geoclimatic types assured a good test of feasibility of field operations and provided a broad base of observation, but the sample sizes were too small to allow separate estimates for these strata. Also, because of this arbitrary limitation of our study, our results cannot be used to characterize the Chowan River basin, but apply only to the portions within which we worked.

If often happens, as it did here, that it is impossible or impractical to extend probability sampling over the entire spatial or temporal universe. For example, our definition of small drainage basins (below) requires a road crossing as a sampling point. The spatial sampling frame covering the small drainages in the Chowan River basin as defined included 61 percent of the total basin area. Those small drainages excluded include those that, before crossing a road, join tributaries that have already been listed in their headwaters. Also excluded are any areas draining directly into such tributaries or into the main stream, as well as the surface area of the tributaries and the main stream. In addition, certain sites chosen on a map may not be useful in the field either because they are inaccessible or for other reasons. Finally, there may be mistakes in the map and unrecorded drainages may exist. Thus the scale of the map and the policies of the cartographer become an element in the specification of the problem.

For this reason, it would be important to use the same kind of map for comparative studies.

Certain exclusions were also made in the time sampling frame. For example, following an almost universal practice we confined all of our sampling activities to the daylight hours, even though it is known that dissolved oxygen and some biological parameters may differ from day to night. We included weekends and holidays in the sampling schedule, even though many studies do not.

In principle, this problem of possible exclusions from the universe under study may be met in two ways. First, and probably most desirable, is to subdivide, or stratify the universe, and cover the more difficult portions with different methods and perhaps lower sampling intensity. For example, it would be possible, though expensive and difficult, to sample at night, and probably the excluded small drainages could be covered by using different methods. But to make such a complete study would take resources from the rest of the study. The second, and more common method of meeting the problem, is to clearly define the universe to include only the parts studied. Then, after the study is completed, the investigator may state his opinion as to how far the findings should be extended, making it clear that any extension beyond the areas sampled is by judgement unsupported by data.

There are advantages to a complete coverage of a universe. There is no need then to qualify the results concerning portions omitted or to justify the extension of the conclusions to the entire universe unsupported by anything but opinion. There may in fact be real differences between the more accessible and the less accessible portions of a river basin and a complete study may make these known. On the other hand, a complete study is often costly, wearing on personnel, and may take resources away from areas of primary interest. Further, if studies of other workers have covered only part of the universe, one must be careful to stratify a more complete study so that partial results may be compared directly.

Sampling Frames

Separate frames were drawn up for sampling in space and in time. Sampling in space was carried out on four U.S.G.S. 1:250,000 topographic maps (NJ17-9 Roanoke 1971; NJ17-12 Greensboro 1966; NJ18-7 Richmond 1974; NJ18-10 Norfolk 1973). On each map all of the small drainage basins in the Chowan River basin were outlined according to our definition which was:

> "Start at origin of stream, trace down to road crossing that defines the single largest basin in the range 1.3-90.6 square kilometers (0.5-35 square miles); do not count as a road crossing the situation where a bridge crosses an impoundment but do count as a road crossing a road on top of a dam; omit a basin if the only streams

> are marked 'dry' or 'intermittent'; trace basin boundary by topography, otherwise by roads or railroads, otherwise divide equally between streams."

One could eliminate any small basins that are primarily urban or that receive major point discharge if the emphasis is to be on rural runoff. Alternatively, all small basins as defined might be listed, as here, where urban was distinguished on the basis that a substantial portion of the basin fell within city limits as indicated on the map.

Each such small basin was outlined on the map and identified with a serial number; the size as determined by planimeter was recorded as well as the identity of the tributary system and whether rural or urban.

At this stage it would be possible to divide the river basin into several subareas or sampling strata. The objective of such stratification might be to reduce the variability of the streams being sampled, to derive estimates for subareas, or to exercise some control over the distribution of sample sites. This question did not arise in the present feasibility study which was confined to four minor, arbitrarily selected portions of the Chowan River basin.

The frame for sampling in time is a calendar. Most environmental parameters have a strong seasonal element and therefore stratification in time is desirable. In planning this study it was reasoned that the shorter the periods used as time strata, the more they would remove of any seasonal variation. For this reason, time strata were planned to be no longer than necessary to provide two visits per period to the number of sites to be covered; this required 4 weeks. The field schedule was planned to provide for certain ability to cover all sites twice during each period. Although 3 trips of 3 days each were thought adequate to cover all sites and return samples, a further day was allowed each trip for emergency use if needed. Six such 4-day intervals allowed for visiting each site twice and a seventh equal interval allowed time for repair of equipment and time off for personnel. Also, 7 periods of 4 days resulted in each period starting on a different day of the week, thus balancing any day-of-the-week effect.

Drawing the Sample and Planning the Field Schedule

A sample of sites is drawn from the serially numbered list of small basins. In our case, the sites were drawn from a complete list of all sites in the chosen work areas but in principle, the sample would be drawn from the entire river basin, or a designated number would be selected from each of the strata if these were set up.

In drawing such a sample, a table of random numbers is used. With a relatively small universe (here 397 possible sites) the items of the universe may be listed by serial number and numbers of sufficient digits drawn from a random number table to identify the sample sites, ignoring all numbers greater than the largest serial number and any random numbers that are repeated. For a larger universe it may be more convenient to assign a random number to each member of the list and then re-sort the list in order of random number and accept the first so many as a designated sample. This last operation is most easily carried out by computer.

Once a sample of sites has been chosen, there is a question of the order in which these are to be visited on any trip into the field. If the sites are always covered in the same order, then each site may always be visited at about the same time of day, thus confounding any time of day differences with site differences. Further, the same set of sites will be always visited on the same day, thus increasing correlations among sites. For statistical purposes the best method would be to visit the sites in a completely random order, rerandomizing this order for each visit. But with sites spread over an entire river basin such a plan would be impractical. As a compromise, we grouped the 35 sites to be covered into 3 "routes" each of which constituted a practical unit of field effort, requiring three work days to leave Raleigh, visit the sites, and return. For any one route, several practical orders of visiting the sites were set up and one of these chosen at random for any one visit.

In laying out the field schedule (Table 4) the interval for repair and rest was allocated first at random to 1 of the 7 possible positions within the 28-day period. Then, of the remaining six 4-day intervals, the first 3 were allocated to the first visit and the rest to the second visit. The 3 routes were assigned at random to each set of three 4-day intervals (using a random permutation). Then, within each route an order of visiting the sites was designated.

Use of Logarithmic Transformation

Among the problems of data management is the fact that the logarithmic transformation was used throughout the analyses of these data. The logarithmic transformation was used for several reasons. First, variation in a number of measurements and especially in the measurement of flow can more reasonably be thought of as proportional or multiplicative rather than as additive in an absolute sense. Statistical methods used here are based upon additive linear models, and multiplicative models become additive when the data are log-transformed. The distributions of many of the data were strongly skewed with relatively few large values and many small values; use of the logarithmic transformation tends to bring such distribution closer to the normal and thus more tractable of statistical manipulation. Further, standard statistical tests such as the analysis of variance assume that the standard deviation is independent of the mean while with many of these measurements the standard deviation was obviously correlated with the mean when subsets of the data were examined. Use of the logarithmic transformation makes the standard deviation independent of the mean value under these conditions.

Use of the logarithmic transformation creates some difficulties in the interpretation of results. When a transformation is used, tests of hypotheses and statements of confidence intervals must be carried out

TABLE 4. EXAMPLE OF FIELD SAMPLING SCHEDULE (PERIOD 27, VISITS 53 AND 54) SHOWING ORDER OF VISIT TO SITES

Year Month Visit Number	Day	Route	Group	Alternate or NH3 sample	Period 27 (sites to be sampled from left to right)
1976					
Nov	28		C		M2-17A; M2-18K; M2-19W
53	29	III	A	NH3	M3-20K; M3-28Y; M3-22M; M3-23A; M3-24W; M3-25X
	30		B		M7-27W; M1-26W
Dec	1				
53	2		B		W10-16W; W8-15W
	3	I	A	A	P10-6Y; P10-1A; P10-2B; P10-3K; P10-4W; P10-29Z
	4		C		W3-13W
	5				
53	6		A		U1-32W; U8-30W; U4-31W
	7	II	B	A	P11-9W; P11-7A; P11-8K; W4-14W
	8		C		P13-10W; P8-11K; P8-12W
	9				
	10				
	11	off			
	12				
	13				
54	14		C		W3-13W
	15	I	A	NH3	P10-29Z; P10-1A; P10-2B; P10-3K; P10-4W; P10-6Y
	16		B		W10-16W; W8-15W
	17				
54	18		A		U4-31W; U8-30W; U1-32W
	19	II	B		P11-7A; P11-8K; P11-9W; W4-14W
	20		C		P13-10W; P8-11K; P8-12W
	21				
54	22		C		M2-17A; M2-18K; M2-19W
	23	III	A	A	M3-28X; M3-22M; M3-23A; M3-24W; M3-25X; M3-20K
	24		B		M7-27W; M1-26W
	25				

Note: Geoclimatic codes changed in manuscript: U is now A, M is now F.

with the transformed data. When the mean value of a series of log-transformed data is detransformed, the result is the geometric mean rather than the arithmetic mean. Most readers are accustomed to reasoning from the arithmetic mean; the geometric mean is always smaller than the arithmetic mean by a factor that depends upon the variability of the data (if the data are truly log-normal). Therefore, to allow comparison between different studies and allow interpretation of the data, it is desirable to state both the arithmetic mean and the geometric mean, and not the mean in logarithmic units because this is difficult to translate to the proper scale. Further, detransformed values of the standard deviation, standard error, or confidence interval must be read as a factor to be multiplied by or divided into the geometric mean because in the log-transformed form such statistics are understood to be added or subtracted. Thus, in this way the standard error is stated as a multiple of the (geometric) mean value.

The proportional standard error, that is, the standard error divided by the mean, is often used as a statement of relative precision of an estimate. This quantity is also sometimes called the coefficient of variation, although that usage is not followed here because it generates confusion with an identically named quantity, the standard deviation divided by the mean. When using logarithmically transformed data, an equivalent to the proportional standard error may be derived by taking the anti-logarithm of the standard error, and subtracting unity. Extensive use of this quantity is made in comparing relative precision of different sampling plans later in this study. For a feasibility study such as this, this value of the proportional standard error has the great advantage that it does not require the direct calculation of the mean value but may be derived directly from the component variances.

Use of the logarithmic transformation raises a further problem, that of what to do about zero values. At some times during this study, the measurement of flow rate was actually zero either because it was too low to be measured, or because the stream bed was dry, at least in sections. The conventional advice under these conditions is to add unity to each quantity before taking the logarithm, but this seems highly inappropriate when the measurements concerned may be small decimal values. The practice adopted was to substitute for the zero values one-tenth of the lowest recorded non-zero value in the data series.

Missing Data

There were a certain number of cases where data were not recorded. These fell into four categories, the first of which was when the sampling plan called for making the measurement on only part of the visits. For example, ammonia was determined for only one visit per period instead of the usual two. In this case, calculations would have to follow the special design that resulted from this change.

The second category of missing information resulted from no concentrations being measured when there was zero flow. The desired mean concentration was that when there was a flow of water; with no flow, no measurement was made. This constitutes a definition limiting the scope of the study and corresponds to what Cochran (1977) describes as domains of interest. The overall mean value of concentration was calculated without including any value when there was no flow of water. However, when calculating a variance of the mean, a value of zero was substituted for the missing value, following the advice in this reference.

The third category of missing information was when there was a measured non-zero flow but no concentration was measured because of accident, as when the sample was lost. Here a synthetic missing value was substituted, calculated by regression on values at other sites in the same geoclimatic stratum.

Finally, there was the case where flow was not measured for various reasons, most commonly either because flow was too low to be measured, or when flood conditions prevented a measurement. Concentrations measured under these conditions were valid. A flow value was synthesized and substituted, based upon regression on values at other sites.

To synthesize substitute values where data points were missing we used a multiple regression on values for other sites of the same geoclimatic stratum. The regression equation was set up on the basis of available data, and then the missing value was calculated as that expected from the values observed at the other sites. Such missing values constituted a very small percentage of the total number.

Making an Estimate

To calculate the mean value for a study of, say, 1-year duration, first the mean for each of the periods should be calculated and then the annual value calculated as the mean of the period means. Within each period there should be a value, real or synthetic (and possibly zero) for each site visit for flow or for transport but not necessarily a value for concentration.

To estimate a variance and a standard error for such a mean value it is necessary with this sampling design to synthesize a value following the reasoning of the statistical model. The sampling design is based upon repeated use of several randomly selected sites which are sampled at random in time and one cannot calculate a value for the variance in the usual manner, assuming that all measurements are independent. In other words, it is necessary to allow for the fact that the sample size for variability among sites is limited to the number of sites selected, no matter how many times each of these may be visited. The synthesizing of such an error term is carried out in two steps, first, the estimation of the variance components from the field data, and second, the calculation of the standard error, which is presented here mostly as the proportional standard error.

Components of Variance

Components of variance are probably best understood in the context of an analysis of variance and are discussed in a number of textbooks including that of Steel and Torrie (1960; see p. 214 for a mixed model similar to this design). We are concerned with a mixed model where the effect for period is fixed; there is no question of sampling periods, each is represented. All other effects, including sites, visits within periods, the interaction of sites and periods, and the error term, are random effects. This design is laid out in the usual form in Table 5 which shows the average values expected for the mean squares for each of the effects. Variance components are estimated by subtracting the correct mean square values and dividing by the appropriate coefficients (Table 5 includes a numerical example).

Variance components were estimated separately for each of the geoclimatic strata, resulting in four different values for each water quality parameter, one for each stratum, as illustrated for yield of water in Table 6. As shown in this table, these values varied considerably from stratum to stratum, each being based upon a very small sample number of sites. For further work, the arithmetic mean of these four values was used. In principle it would be possible to proceed with the information from each stratum separately and then combine these into a weighted average. We chose to average the components and then to discuss the problem as though it were one of simple random sampling, unstratified in space. This step was taken because of the high variability, the small sample sizes within each stratum, and for lack of good evidence that the components differed among strata (pair-wise F-test of variance ratio).

While it is quite possible to calculate variance components by hand as illustrated in Table 5, it is more practical with large amounts of data to use a computer program as we did. The SAS program used calculated the components as though all effects including periods were completely random, and not as a mixed model, with the result that variance components for sites had to be recalculated by hand where the interaction component was non-zero.

Estimating Standard Error and Comparing Precision

Estimates of the standard error of the estimate for a particular study may now be calculated, given the values for the components of variance. These values are substituted in formula (2), which is:

$$\text{var } \bar{x} = (\sigma^2_S/s) + (\sigma^2_{(S\Pi)}/sp) + (\sigma^2_V/pv) + (\sigma^2_e/spv) \qquad (2)$$

The constants in the denominators depend upon the survey design; in our study there were 15 sites (s), 13 periods (p), and 2 visits per period (v). Thus using the information on water yield from Table 6 the variance of an estimate for a 1-year study would be:

TABLE 5. AVERAGE VALUES FOR MEAN SQUARES AND EXAMPLE (LOG-TRANSFORMED WATER YIELD DATA FROM POORLY-DRAINED COASTAL PLAIN), SHOWING ESTIMATION OF VARIANCE COMPONENTS

Source of variability	Example		Average value of mean square
	Degrees of freedom	Mean square	
Site	3	17.9169	$\sigma_e^2 + pv\sigma_S^2$
Period	25	5.3020	$\sigma_e^2 + v\sigma_{(S\Pi)}^2 + s\sigma_V^2 + sv\frac{\Sigma\Pi^2}{p-1}$
Site x Period	75	0.9583	$\sigma_e^2 + v\sigma_{(S\Pi)}^2$
Visit within Period	78	1.0051	$\sigma_e^2 + s\sigma_V^2$
Error	207	0.2961	σ_e^2

Estimates:

Variance component for Site = (17.9169-0.2961)/52 = 0.3389

Variance component for Period = (5.3020-0.9583-1.0051+0.2961)/8 = 0.4543

Variance component for Site x Period = (0.9583-0.2961)/2 = 0.3311

Variance component for Visit within Period = (1.0051-0.2961)/4 = 0.1772

Note: Data are for s = 4 sites, p = 26 periods of 4 weeks (2 years), and v = 2 visits per period; recall that Period is a fixed effect.

TABLE 6. EXAMPLE SHOWING VARIANCE COMPONENTS AS DETERMINED FROM EACH OF THE 4 GEOCLIMATIC STRATA, AND MEAN VALUES, FOR WATER YIELD (DATA LOG-TRANSFORMED)

Land-use stratum	Number of sites	Components of variance for:			
		Site	Site x Period	Visit within Period	Error
Well-drained coastal plain	4	0.2007	0.2163	0.6465	1.2521
Poorly-drained coastal plain	4	0.3389	0.3311	0.1772	0.2961
Silvicultural piedmont	4	0.0600	0.0900	0.2636	0.3771
Agricultural piedmont	3	0.2142	0.2709	0.1782	0.1691
Mean	15	0.2034	0.2271	0.3164	0.5236

$$\text{var } \bar{x} = (0.2034/15) + (0.2271/195) + (0.3164/26) + (0.5236/390)$$

$$= 0.02824.$$

The standard error of the estimate would be the square root of this quantity, or 0.1680. The anti-logarithm of 0.1680 is 1.472 and subtracting 1, the proportional standard error is 0.472. Similar calculations were made for other parameters.

The primary objective of this study, however, was not to calculate estimates and standard errors for this actual study, but rather to compare the precision obtainable under optimal allocation of effort with various budgets. For example, the budget available for allocation of sampling effort for a design of the kind we used would be $33,291 (as calculated from formula (3); recall that this is in 1975 dollars and that $14,211 must be added as a constant or overhead cost). By coincidence, it happened that for water yield the allocation of effort in the design we used was exactly that to be calculated as optimal for this budget from formulas (4) and (5), that is, two visits per period and 15 sites. Now imagine that we asked what would happen to the precision if we doubled the budget to a total of $95,004 (with $80,793 available for sampling). Here the optimal allocation would be 3 visits per period and 25 sites. Recalculating the variance of the estimate:

$$\text{var } \bar{x} = (0.2034/25) + (0.2271/325) + (0.3164/39) + (0.5236/975)$$

$$= 0.01748.$$

Here the standard error would be 0.1322 and the proportional standard error 0.356. Note, incidentally, that the ratio of the standard errors (0.1322/0.1680) is about 0.79 instead about 0.71, the value expected when doubling sampling effort under simple random sampling. Neither the number of sites nor the number of visits could be doubled, rather, each was increased one-half or two-thirds.

Similar calculations were made for the water quality parameters studied here at a range of budgets between about $28,000 and $269,000; in one comparison the upper level was $497,000. The particular budget sizes to be compared were chosen in anticipation of also calculating precision from use of automated sampling, where the budget would have to be increased in the large increment of $13,415.90, the cost of adding a single automated site. Thus the lowest value, $27,854, was the sum of the constant cost for automated sampling ($14,438) plus the cost of a single automated site. Statistically speaking, such a design would be impractical for any study where an estimate of variance was needed because there would be only a single value for site, but this lowest budget could be used with grab sampling and it provided a convenient starting point for the range of budgets to be examined.

The precision attainable was calculated under the present design at different budget levels and also under designs without stratification or where the length of periods was changed. In each case the procedure was the same as above. Using the components of variance calculated from our field experience, the optimal allocation as to number of sites and number of visits was calculated using formulas (4) and (5) and then a proportional standard error was synthesized. This allowed a comparison to be made under optimal conditions at the same budget levels.

RESULTS

Results are reported here for drawing up the sampling frame, for some incidental investigations on the usefulness of stratification in time and the effect of changing length of periods, then on the calculation of components of variance and on analysis of costs. This information allows the exploration next of the relative precision attainable at different budgets, and a comparison of the cost-efficiency of grab sampling as compared to automated sampling.

The Sampling Frame

The sampling frame was drawn up for the entire Chowan River basin by delineating each of 397 small drainage basins on U.S.G.S. 1:250,000 topographic maps, determining the area of each basin by planimeter, numbering and listing the basins according to major tributary of the river. This frame was constructed to confirm the feasibility of this part of the sampling approach and determine the cost of such an operation even though the frame itself was not used in our study. Constructing such a frame is not inexpensive; the 100 hours of technician time required made up by far the largest single item in the cost of planning the study. Table 7 shows the distribution of these small drainage basins according to tributary, whether rural or urban, and by size class (with limits set arbitrarily to divide the total small-basin area about equally). The table also repeats the definition according to which the basins were outlined on the map. Such small basins accounted for 61 percent of the total area of the Chowan River basin.

Effect of Stratification in Time

The effect of stratification on precision was considered in two ways, first, by contrasting precision attained when using stratification (as in our design) with results using no stratification, and second, considering the effect of using time strata of differing length.

The relative precision of grab sampling with and without stratification in time is shown in Table 8 as proportional standard error. Optimal allocation of effort was assumed whether with or without stratification; this distribution of effort is recorded for 3 budget levels. In most cases, stratification in time seemed to provide appreciable advantage. For example, with flow measurements this stratification reduced proportional standard error by 15 percent at the lowest budget and by 24 percent

TABLE 7. SMALL DRAINAGE BASINS* OF THE CHOWAN RIVER SYSTEM, LISTED BY TRIBUTARY, SIZE AND WHETHER RURAL (R), URBAN (U)

Small basin area km² (mi²)	Blackwater River		Nottoway River		Somerton Creek		Meherrin River		Wiccacon Creek		Other		Total			Percent of total Chowan basin area†
	R	U	R	U	R	U	R	U	R	U	R	U	R	U	Sum	
< 2.6 (≤ 1)	16	-	31	-	-	-	15	1	7	-	6	-	75	1	76	1.4
5.2-20.7 (2-8)	27	5	77	2	4	-	54	5	9	-	11	1	182	13	195	15.6
23.3-38.8 (9-15)	12	-	13	4	4	-	20	2	2	1	3	-	54	7	61	14.7
41.4-57.0 (16-22)	4	3	13	1	1	1	6	3	1	-	2	-	27	8	35	13.3
59.6-90.6 (23-35)	3	1	10	2	-	-	7	3	1	1	2	-	23	7	30	16.1
Total	62	9	144	9	9	1	102	14	20	2	24	1	361	36	397	61.1
											Remainder of Chowan basin					38.9
Area in small basins km² R	1072		2504		215		2010		306		470		6577			
U	259		350		57		469		93		18		1246			
												Total	7823			

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* Data from planimeter measurement of small basins outlined on U.S.G.S. 1:250,000 topographic map. Rule for defining a small basin: "Start at origin of stream, trace down to the road crossing that defines the single largest basin in the range 1.3-90.6 square kilometers (0.5-35.0 square miles); do not count a bridge crossing an impoundment as a road but do count a road on a dam; omit if the only streams are marked "dry" or "intermittent"; trace basin boundary by topography, otherwise by roads or railroads, otherwise divide equally." Urban was differentiated from rural on the basis that a substantial portion of the basin fell within city limits as indicated on the map.

† Total area of Chowan basin -- 12,802 km² (4,943 mi²).

TABLE 8. PRECISION OF MEASUREMENT (AS PROPORTIONAL STANDARD ERROR*) TO BE EXPECTED WITH GRAB SAMPLING WITH AND WITHOUT STRATIFICATION IN TIME (PERIODS), IN EACH CASE WITH OPTIMAL ALLOCATION OF SAMPLING EFFORT, SHOWN AS (NO. OF SITES/TOTAL NO. OF VISITS PER SITE) AND UNDER 3 BUDGET SIZES

	Stratified into time periods?	Approximate budget for a one-year study		
		$28,000	$108,000	$269,000
Flow of Water	yes	0.906(6/26)	0.412(42/26)	0.299(60/52)
	no	1.060(7/22)	0.538(20/57)	0.394(34/93)
Yield of Water	yes	0.694(6/26)	0.340(29/39)	0.254(48/65)
	no	0.837(6/29)	0.454(15/75)	0.332(26/123)
Concentration of:				
Nitrate Nitrogen	yes	0.304(6/26)	0.110(42/26)	0.069(115/26)
	no	0.187(25/5)	0.104(79/13)	0.079(134/22)
Kjeldahl Nitrogen	yes	0.115(4/39)	0.064(11/104)	0.048(20/156)
	no	0.119(3/55)	0.067(8/143)	0.050(14/236)
Total Phosphorus	yes	0.148(6/26)	0.080(29/39)	0.061(40/78)
	no	0.152(7/23)	0.087(19/60)	0.066(32/98)
Chloride	yes	0.104(6/26)	0.054(29/39)	0.042(48/65)
	no	0.106(8/21)	0.062(21/55)	0.047(35/90)

* Log-transformed data; proportional standard error is expressed here as antilog standard error, minus 1. The smaller this quantity, the better the precision.

at the highest. For nitrate nitrogen, however, the situation was reversed with the non-stratified study providing a potential of considerably better precision at the lowest level of budget. This anomaly arose because of the relative predominance of the variance component for site which, as is pointed out later, was not well accomodated by the particular sampling design used. At the highest budget considered for the same material, the ratio was reversed with the stratified design having a proportional standard error 13 percent less than the unstratified, thus resembling the balance with the other parameters.

The effect on the variance components of changing the length of period from four weeks to 10 weeks was explored empirically with the data of this study. This was possible because our design called for one visit to each site within each interval of about two weeks and while the original plan was for two visits per four-week period, it was possible to redraw the lines defining periods and include successively more visits, up to five, within a period. This manipulation of the data was carried out with only three of the variables, flow of water and concentration of nitrate nitrogen and Kjeldahl nitrogen, as shown in Table 9. The proportional standard error was calculated on the basis of a one-year study assuming 15 sites and a total of 26 visits per site, divided into periods of varying lengths. This table also lists the equivalent component for periods which is not listed in other tables because it is not of itself a contributing element to the variance of the mean; in fact, the object of stratification in time is to eliminate this element. As period length increased, with Kjeldahl nitrogen concentration there was the expected decrease in the component for periods with a corresponding increase in the component for visit within periods; there was no consistent change with flow of water or concentration of nitrate nitrogen.

TABLE 9. EMPIRICAL EXPLORATION OF EFFECT ON VARIANCE COMPONENTS OF CHANGING FROM 2 VISITS (4 WEEKS) TO 5 VISITS (10 WEEKS) PER PERIOD FOR THE SAME SET OF DATA

		Variance components for:					Proportional standard error†
	Length of period in visits	Period*	Site	Site x Period	Visit within Period	Error	
Flow of Water	2	0.6258	0.3573	0.1955	0.3394	0.5356	0.578
	3	0.6814	0.3611	0.1172	0.3208	0.6220	0.575
	4	0.6066	0.3574	0.1446	0.3877	0.5950	0.601
	5	0.6903	0.3726	0.1649	0.3368	0.5952	0.598
Nitrate Nitrogen Concentration	2	0.0082	0.0766	0.0137	0.0043	0.0256	0.184
	3	0.0082	0.0762	0.0087	0.0035	0.0314	0.184
	4	0.0058	0.0767	0.0095	0.0058	0.0303	0.186
	5	0.0070	0.0758	0.0108	0.0056	0.0304	0.186
Kjeldahl Nitrogen Concentration	2	0.0201	0.0032	0.0100	0.0312	0.0686	0.098
	3	0.0178	0.0032	0.0057	0.0306	0.0747	0.097
	4	0.0029	0.0032	0.0052	0.0490	0.0741	0.118
	5	0.0072	0.0033	0.0146	0.0420	0.0647	0.114

* Period is a fixed effect.

† Using design of present study, i.e., 15 sites with a total of 26 visits per site, for 1 year. Log-transformed data; proportional standard error is expressed here as antilog standard error, minus 1. The smaller this quantity, the better the relative precision.

Components of Variance

Components of variance based upon the present study are listed in Table 10, which also shows the proportional standard error for a one-year

TABLE 10. COMPONENTS OF VARIANCE AND PROPORTIONAL STANDARD ERROR* FOR SELECTED PARAMETERS OF WATER QUALITY IN THE CHOWAN RIVER BASIN; COMPONENTS ARE AVERAGES BASED ON 15 SITES, EACH VISITED 52 TIMES IN THE WELL-DRAINED COASTAL PLAIN (4 SITES), THE POORLY-DRAINED COASTAL PLAIN (4 SITES), THE SILVICULTURAL PIEDMONT (4 SITES) AND 38 TIMES IN THE AGRICULTURAL PIEDMONT (3 SITES), DATA LOG-TRANSFORMED

	Variance components for:				Proportional
	Site	Site x Period	Visit within Period	Error	standard error*
Flow of Water	0.3573	0.1955	0.3394	0.5356	0.578
Yield of Water	0.2034	0.2271	0.3164	0.5236	0.472
Concentration of:					
Nitrate Nitrogen	0.0766	0.0137	0.0043	0.0256	0.184
Kjeldahl Nitrogen	0.0032	0.0100	0.0312	0.0686	0.098
Total Phosphorus	0.0126	0.0219	0.0226	0.0555	0.107
Chloride	0.0071	0.0104	0.0092	0.0258	0.074
Transport of:					
Nitrate Nitrogen	0.9507	0.3259	0.7271	1.0553	1.039
Kjeldahl Nitrogen	0.3481	0.0490	0.4553	1.0869	0.619
Total Phosphorus	0.4103	0.2144	0.4044	0.5820	0.634
Chloride	0.3274	0.1808	0.2941	0.4724	0.541
Yield of:					
Nitrate Nitrogen	0.8282	0.3467	0.6570	0.9595	0.955
Kjeldahl Nitrogen	0.1649	0.0547	0.4070	1.0366	0.486
Total Phosphorus	0.1870	0.2321	0.3721	0.5521	0.484
Chloride	0.1926	0.1984	0.2642	0.4462	0.441

* Using the design of present study, i.e., 15 sites, 13 periods, each with 2 visits per site for 1 year. Log-transformed data; proportional standard error is expressed here as antilog standard error, minus 1. The smaller this quantity, the better the relative precision.

survey based on these components and using the present design, i.e., 15 sites, 13 periods of 4 weeks each, each with 2 visits per site. These components of variance are averages of values calculated for each of the four geoclimatic study areas and the proportional standard error is calculated from these average values as though there were no stratification in space. Components of variance were calculated here for a selected set of parameters, including flow of water, yield of water per unit area of drainage, and concentration, transport and yield of nitrate nitrogen, Kjeldahl nitrogen, total phosphorus and chloride. This set of variables was then examined in greater detail with reference to planning an efficient study at each of a range of budget levels.

These components of variance provide part of the raw materials for calculating the optimal allocation of sampling effort. Information on cost is also required; this is presented next.

Costs

Information on cost is presented in four tables, two each for grab and for automated sampling. Tables 11 and 12 present the information on grab sampling and Tables 13 and 14 the data on automated sampling; in each pair the first table presents only the personnel costs and the second table the total costs including personnel so that the non-personnel costs may be obtained by subtraction. Each table assumes a one-year study of water quality based upon probability sampling. Costs are presented under the three headings of constant (overhead) cost, the cost per site established, and the cost per single visit to an established site. All costs are stated here in 1975 dollars; these values must be expanded using an appropriate multiplier if guidance is to be sought here in planning other studies.

The information on costs that is used in the further work with optimal allocation may be summarized as the following values, which are treated hereinafter as constants:

	Grab sampling	Automated sampling
Fixed cost (c_1)	\$14,211.25	\$14,438.09
Per-site cost (c_s)	153.18	(1) 5,667.38 (2) 7,277.30
Per-visit cost (c_v)	79.47	(1) 149.01 (2) 32.89

For automated sampling, the per-site and per-visit costs were calculated two ways, (1), to fit the sampling schedule used in our study, and (2), counting field sampling costs of 52 weekly service visits as per-site costs, reducing the "per-visit" costs to those of chemical and statistical analysis of a single water sample.

Fixed costs were approximately the same for both types of sampling. The per-site cost was much greater for the automated sampling because of the instruments and construction required at each site. Depending upon how service trips were accounted, the per-visit cost for automated sampling was either about twice as great or about half as much as that for grab sampling.

TABLE 11. PERSONNEL COSTS FOR A ONE-YEAR GRAB-SAMPLING STUDY OF WATER QUALITY OF A RIVER BASIN BASED ON A PROBABILITY SAMPLING OF SITES AND VISITS; COSTS* ESTIMATED FROM EXPERIENCE IN THE CHOWAN RIVER RURAL RUNOFF STUDY

Item	Constant cost	Per site cost	Per visit cost
Administration	$1,919.94	$ 2.94	$ 0
Planning	664.76	0	.08
Chemical analysis (contracted)	384.50	0	.46
Field exploration, construction	0	62.49	0
Field sampling	615.20	7.69	18.86
Data management:			
using our computer programs	856.16	0	2.05
not using our computer programs	2,417.10	0	2.05
Subtotal:			
using our computer programs	$4,440.56	$73.12	$21.45
not using our computer programs	6,001.50	73.12	21.45
Indirect costs: Add 50 percent of total personnel cost.			
Example: Total personnel cost if our computer programs are not used			
Total without indirect costs:	$6,001.50	$73.12	$21.45
Total including indirect costs:	$9,002.25	$109.68	$32.18

* Costs in 1975 dollars.

TABLE 12. TOTAL COSTS (INCLUDING PERSONNEL) FOR A ONE-YEAR GRAB-SAMPLING STUDY OF WATER QUALITY OF A RIVER BASIN BASED ON A PROBABILITY SAMPLING OF SITES AND VISITS; COSTS* ESTIMATED FROM EXPERIENCE IN THE CHOWAN RIVER RURAL RUNOFF STUDY

Item	Constant cost	Per site cost	Per visit cost
Administration	$ 1,919.94	$ 2.94	$ 0
Planning	864.76	0	.08
Chemical analysis (contracted)	2,584.50	0	30.56
Field exploration, construction	50.00	101.49	.75
Field sampling	2,649.20	12.19	30.96
Data management:			
using our computer programs	1,371.16	0	6.39
not using our computer programs	3,142.10	0	6.39
Subtotal:			
using our computer programs	$ 9,439.56	$116.62	$68.74
not using our computer programs	11,210.50	116.62	68.74
Indirect costs: Add 50 percent of total personnel cost.			
Example: Total cost (including personnel) if our computer programs are not used			
Total without indirect costs:	$11,210.50	$116.62	$68.74
Total including indirect costs:	$14,211.25	$153.18	$79.47

* Costs in 1975 dollars.

TABLE 13. PERSONNEL COSTS FOR A ONE-YEAR AUTOMATED SAMPLING STUDY OF WATER QUALITY OF A RIVER BASIN BASED ON A PROBABILITY SAMPLING OF SITES; COSTS* ESTIMATED FROM EXPERIENCE IN THE CHOWAN RIVER RURAL RUNOFF STUDY

Item	Constant cost	Per site cost	Per visit cost
Administration	$1,919.94	$ 2.94	$ 0
Planning	664.76	0	.08
Chemical analysis (contracted)	384.50	0	.46
Field exploration, construction	184.56	193.29	0
Field sampling	615.20	7.69	18.86
Data management:			
using our computer program	856.16	0	2.05
not using our computer program	2,417.10	0	2.05
Subtotal:			
using our computer programs	$4,625.12	$203.92	$21.45
not using our computer programs	6,186.06	203.92	21.45
Overhead: Add 50 percent of total personnel cost.			
Example: Total cost if our computer programs are not used			
Total without overhead:	$6,186.06	$203.92	$21.45
Total including overhead:	$9,279.09	$305.88	$32.18

* Costs in 1975 dollars.

TABLE 14. TOTAL COSTS (INCLUDING PERSONNEL) FOR A ONE-YEAR AUTOMATED SAMPLING STUDY OF WATER QUALITY ON A RIVER BASIN BASED ON A PROBABILITY SAMPLING OF SITES; COSTS[*] ESTIMATED FROM EXPERIENCE IN THE CHOWAN RIVER RURAL RUNOFF STUDY

Item	Constant cost	Per site cost	Per visit cost
Administration	$ 1,919.94	$ 2.94	$ 0
Planning	864.76	0	.08
Chemical analysis (contracted)	2,584.50	0	100.85[†]
Field exploration, construction	184.56	5,550.29[‡]	0
Field sampling	2,649.20	12.19	30.96[‡]
Data management:			
using our computer programs	1,371.16	0	6.39
not using our computer programs	3,142.10	0	6.39
Subtotal:			
using our computer programs	$ 9,574.12	$ 5,565.42	$138.28
not using our computer programs	11,345.06	5,565.42	138.28
Overhead: Add 50 percent of total personnel cost.			
Example: Total cost if our computer programs are not used			
Total without overhead:	$11,345.06	$ 5,565.42	$138.28
Total including overhead:	$14,438.09	$ 5,667.38	$149.01
Annual cost per site, assuming weekly visits		$13,415.90	

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[*] Costs in 1975 dollars.

[†] On the basis of 3.3 water samples per weekly visit.

[‡] The total per-site cost of an automated sampler must include not only this cost of the instrument and construction needed for its installation but also the cost of servicing (number of annual service trips multiplied by per-visit cost of field sampling, above).

Precision Attainable under Different Budgets

In considering the question of relative precision at different budgetary levels, budgets were set according to costs of automated sampling, with the increment of increase being the cost of installing and operating one automated site ($13,415.90). The lowest budget considered, $27,854, was thus the sum of the constant cost for automated sampling ($14,438) and the one-year cost of a single automated site. Budgets set in this fashion and examined as to the potential precision of measurement both by grab sampling and by automated sampling ranged over almost a ten-fold span from $28,000 to $269,000 (and in one instance, to $497,000).

For each such budget, the optimal allocation of grab sampling sites and visits was estimated and then the attainable precision of determination was calculated as the proportional standard error, using the variance components already presented. Results of this process are presented in Table 15 which shows for each of the parameters under each of five budgets the proportional standard error and the optimal allocation of effort into sites and visits, for a one-year study. It is clear from this table that while respectable precision may be obtained with a low budget for concentration of Kjeldahl nitrogen, total phosphorus or chloride, that a higher budget would be required for the same precision with nitrate nitrogen concentration, and that even with the highest budget considered here, precision would not be good with either flow or yield of water (though yield could be measured with better precision than flow, as should be expected). Equally poor precision characterizes either transport or yield of the chemical entities because these values are so strongly influenced by flow. It is also clear that for any given budget, the optimal allocation of sampling effort differs somewhat depending upon the parameter being considered.

Comparing Grab and Automated Sampling

A comparison of the attainable precision of determination when using automated samplers as against grab sampling under equal budget, is presented in Table 16. This table repeats for grab sampling some of the values from the previous table, presents values derived for automated sampling, and extends the range of budgets to about a half-million dollars to demonstrate the convergence of precision which was apparent in the trends of certain data. The variance components used for the automated sampler were those derived for grab sampling, as described in the methods section. Comparisons of grab and automated sampling are made here only for flow and yield of water and the concentrations of the four chemical parameters. For transport and yield of chemicals we lacked a model for combining the variability in flow and concentration but reasoned that such a model should follow closely the trend of the corresponding measurement of water. For yield of water, concentration of nitrate nitrogen, and of total phosphorus these results are shown in graphical form in Figures 7, 8, and 9. From the figures and tables it is clear that superior precision is obtained by grab sampling at lower budgetary levels. While the trends of increasing precision with greater budgets suggests a

TABLE 15. PRECISION OF MEASUREMENT (AS PROPORTIONAL STANDARD ERROR*) TO BE EXPECTED WITH GRAB SAMPLING USING OPTIMAL ALLOCATION OF SAMPLING EFFORT UNDER VARIOUS BUDGET SIZES, SHOWING IN EACH CASE THE ALLOCATION OF EFFORT AS (NO. OF SITES/TOTAL NO. OF VISITS PER SITE)

	Approximate budget for a one-year study				
	$28,000	$55,000	$108,000	$175,000	$269,000
Flow of Water	0.906(6/26)	0.537(18/26)	0.412(42/26)	0.343(50/39)	0.299(60/52)
Yield of Water	0.694(6/26)	0.445(18/26)	0.340(29/39)	0.289(38/52)	0.254(48/65)
Concentration of:					
Nitrate Nitrogen	0.304(6/26)	0.168(18/26)	0.110(42/26)	0.084(73/26)	0.069(115/26)
Kjeldahl Nitrogen	0.115(4/39)	0.079(8/65)	0.064(11/104)	0.055(15/130)	0.048(20/156)
Total Phosphorus	0.148(6/26)	0.102(18/26)	0.080(29/39)	0.069(38/52)	0.061(40/78)
Chloride	0.104(6/26)	0.069(18/26)	0.054(29/39)	0.047(38/52)	0.042(48/65)
Transport of:					
Nitrate Nitrogen	1.781(6/26)	0.952(18/26)	0.692(42/26)	0.573(50/39)	0.496(60/52)
Kjeldahl Nitrogen	0.942(6/26)	0.579(18/26)	0.437(29/39)	0.368(38/52)	0.322(48/65)
Total Phosphorus	0.998(6/26)	0.589(18/26)	0.445(42/26)	0.376(50/39)	0.327(60/52)
Chloride	0.849(6/26)	0.503(18/26)	0.383(29/39)	0.321(50/39)	0.280(60/52)
Yield of:					
Nitrate Nitrogen	1.612(6/26)	0.877(18/26)	0.643(42/26)	0.533(50/39)	0.462(60/52)
Kjeldahl Nitrogen	0.678(6/26)	0.457(12/39)	0.343(22/52)	0.293(30/65)	0.256(34/91)
Total Phosphorus	0.690(6/26)	0.458(18/26)	0.350(22/52)	0.298(30.65)	0.260(40/78)
Chloride	0.653(6/26)	0.414(18/26)	0.317(29/39)	0.270(38/52)	0.237(48/65)

* Log-transformed data; proportional standard error is expressed here as antilog standard error, minus 1. The smaller this quantity, the better the relative precision.

possible convergence for the two types of sampling for some of the parameters, there was only one, yield of water per unit area, where an actual crossing of the lines was observed and this was at a very high budgetary level (Figure 7). These figures also illustrate the relative contribution made by each component of variance to the overall estimate of precision, the variance of the mean.

TABLE 16. PRECISION OF MEASUREMENT (AS PROPORTIONAL STANDARD ERROR*) ATTAINABLE WITH A RANGE OF BUDGETS, USING OPTIMAL ALLOCATION OF EFFORT WITH GRAB SAMPLING (GRAB) AND A STANDARDIZED SCHEDULE OF WEEKLY VISITS TO AUTOMATED SAMPLERS (AUTO.)†

		Approximate budget for a one-year study					
		$28,000	$55,000	$108,000	$175,000	$269,000	$497,000
Flow of Water	grab	0.906	0.537	0.412	0.343	0.299	0.249
	auto.	2.896	1.193	0.672	0.481	0.366	0.254
Yield of Water	grab	0.694	0.445	0.340	0.289	0.254	0.212
	auto.	1.755	0.795	0.467	0.340	0.262	0.184
Concentration of:							
Nitrate Nitrogen	grab	0.304	0.168	0.110	0.084	0.069	0.054
	auto.	0.897	0.447	0.274	0.203	0.159	0.113
Kjeldahl Nitrogen	grab	0.115	0.079	0.064	0.055	0.048	0.040
	auto.	0.161	0.094	0.065	0.054	0.047	0.040
Total Phosphorus	grab	0.148	0.102	0.080	0.069	0.061	0.052
	auto.	0.313	0.172	0.112	0.086	0.070	0.054
Chloride	grab	0.104	0.069	0.054	0.047	0.042	0.035
	auto.	0.224	0.125	0.081	0.062	0.050	0.038

* Log-transformed data; proportional standard error is expressed here as antilog standard error, minus 1. The smaller this quantity, the better the relative precision.

† Assuming an average of 3.3 water samples taken per week for chemical analysis.

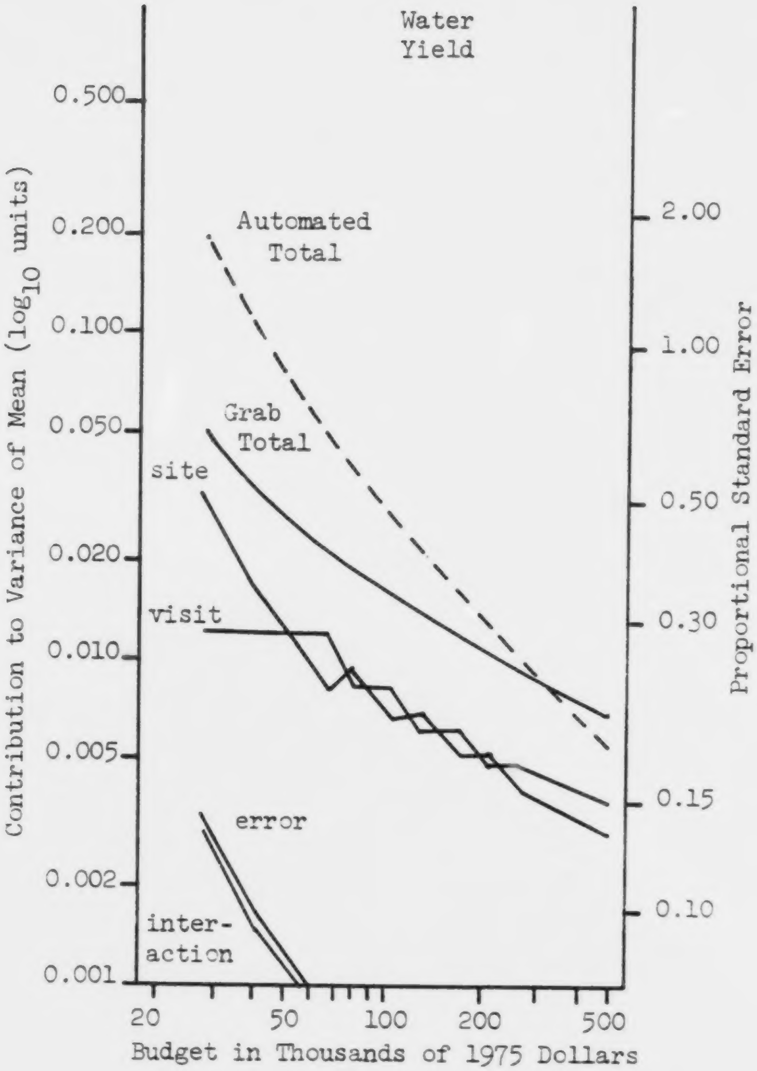

Figure 7. Water yield; precision attainable at different budgets, showing total variance and contribution of components for grab sampling (solid lines) and total variance for automated sampling (dashed line).

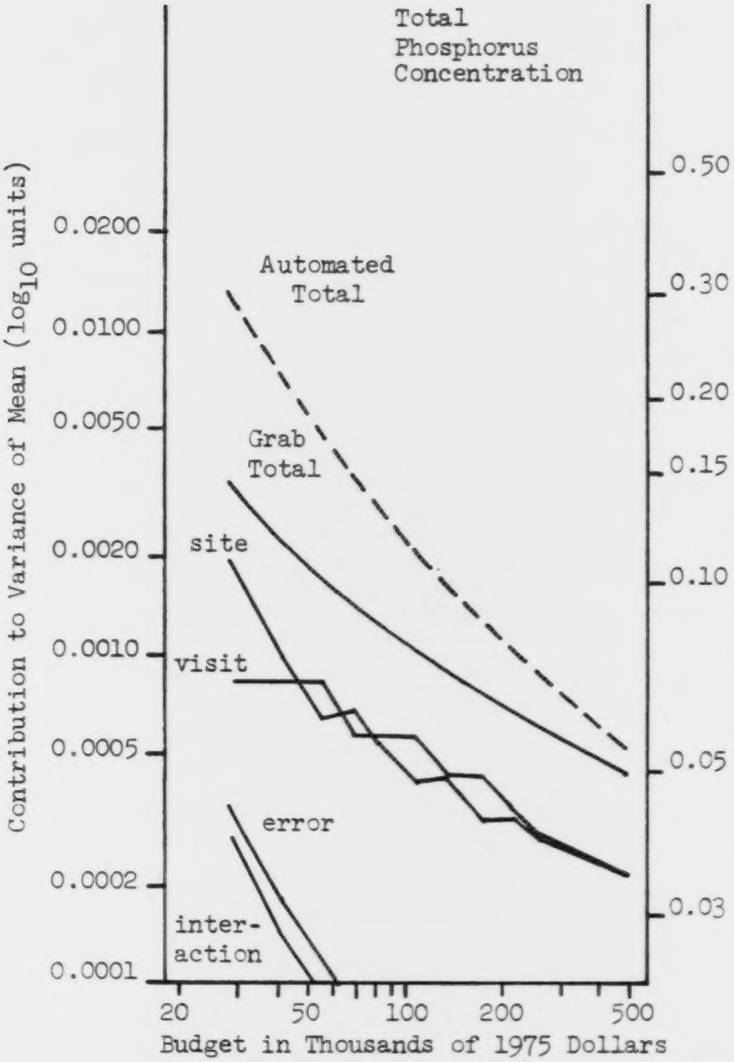

Figure 8. Total phosphorus concentration; precision attainable at different budgets, showing total variance and contributions of components for grab sampling (solid lines) and total variance for automated sampling (dashed line).

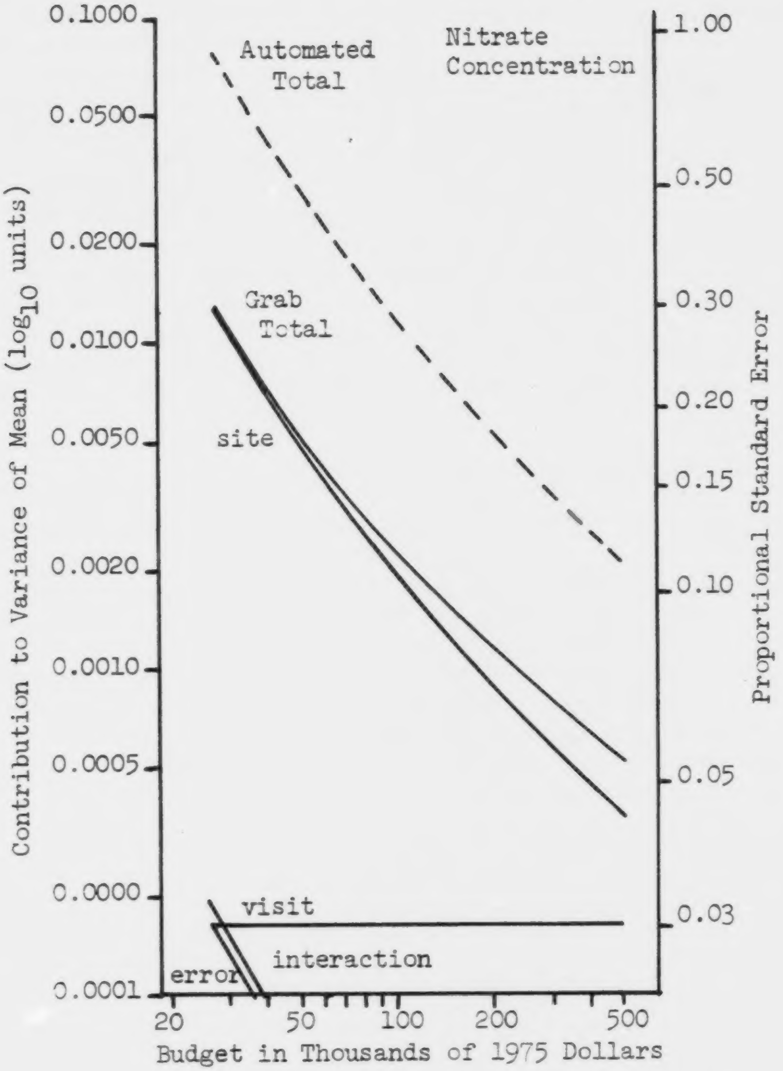

Figure 9. Nitrate nitrogen concentration; precision attainable at different budgets, showing total variance and contributions of components for grab sampling (solid lines and total variance for automated sampling (dashed line).

DISCUSSION

The Sampling Frame

The geographic universe for a study of small drainage basins of the Chowan River system is represented by the enumeration of these basins in Table 7. By definition, any such study would be limited to these basins and would not include certain other important sections of the river basin, for example, small drainages that join larger tributaries before crossing a road, where these tributaries have already been listed in their headwaters. Also excluded are any areas draining directly into such tributaries or into the main stream. Although our definition included the majority of the small drainage basins (it covered 61 percent of the entire basin) there is no doubt that we excluded an important fraction of the total small drainages. If we need to know about these excluded basins then we must devise some other method of study and treat this other part of the river drainage basin as a separate stratum. The methods of study we have used here restrict attention to those small basins that can be defined, and then sampled and studied under the definition.

Effect of Stratification in Time

Stratification in time was used in the design for this study to provide partial control over the seasonal variability expected in water measurements, especially in those of flow. If there are seasonal fluctuations with periods that are relatively long compared to the length of the time stratum, then stratification can improve the precision of estimation by eliminating from the variance the average differences among strata. Such a move does nothing about the short term or random fluctuations which still occur within the time strata. Thus, it would seem that the shorter the time strata can be made, the more of the long-term variability that should be eliminated from the error term.

By and large our findings confirmed this dictum (Table 8). The interesting case of the nitrate nitrogen, however, points out that this rule, "the shorter the time strata the better," must be modified to take account of the type of stratified design to be used. With nitrate the predominant variability was between sites and therefore the best design would emphasize sampling a larger number of sites and this could be done only by reducing the number of visits per period. Our design had fixed 4-week periods and two visits per period (26 per year) were required as the minimum to provide an estimate of sampling error. Under this constraint, only 6 sites could be visited at the lowest ($28,000) budget. In contrast, an unstratified design could provide much better precision at this lowest budget by visiting 25 sites 5 times a year each. This result does not show that stratification of itself would fail here in its usual objective but only that the particular stratified design used was not suited to the parameter being measured. For this parameter, using periods of greater length would probably increase the efficiency of the operation whether or not it resulted in any changes in the variance components.

The empirical exploration of the effect of increasing length of periods (Table 9) failed to show any appreciable change in the variance components for flow and nitrate nitrogen concentration, but for Kjeldahl nitrogen concentration the changes were in the expected direction, that is, a decrease in the variance among periods with increased length of period, accompanied by a corresponding increase in the variance among visits within periods. It was not possible to extend the same type of examination over longer periods with this set of data; one could expect that at some point in increasing the length of periods there would be a stronger effect on the variance components than was found. After all, inclusion of stratification generally yielded better precision than no stratification. The effect of changing length of period is tied up with the structure of the time series for the particular water parameter; apparently Kjeldahl nitrogen concentration fluctuated on a short enough cycle that a change of period length from four to ten weeks altered measurably the distribution of variability between and within periods.

Components of Variance

The components of variance (Table 10) provide insight into the inherent differences in precision among measurements. In a component by component comparison, values associated with the measurement of flow are in the neighborhood of 10 times as great as those for concentrations of chemicals. Adjusting flow to account for the area of the drainage basin reduced the variance component for site by almost half but did not change the others importantly. The components for either transport or yield of a chemical, which combine the variability of flow and concentration (and are dominated by the large values associated with flow) indicate generally poorer overall precision than even the measurement of flow.

Considering the anatomy of the variance of an estimated mean value (Formula 2), for the parameters considered here, the variance components with the greatest influence on the final value are those for sites and for visits within periods. This is true not so much because of numerical value, but because their divisors increase less rapidly with increase in the budget. Further, the balance between components for sites and for visits within period helps determine the optimal allocation of sampling effort between sites and visits. The greater the relative importance of the component for sites, the greater the number of sites that should be covered for efficiency. For example, with nitrate nitrogen the component for sites is over 15 times as great as that for visits within periods and correspondingly Table 8 shows an emphasis on number of sites for nitrate at high budgets with the stratified sampling design; this fact also resulted in the unstratified design being the more efficient at lower budget levels. For Kjeldahl nitrogen the component for visits exceeded that for sites. For phosphorus and for chloride the two components were of about the same magnitude; the same was true for flow and yield of water and consequently, for all transport or yield of chemicals.

Costs

The information on costs of all phases of our study is of central importance to the further analysis of cost-effectiveness. The high cost of establishing one automated site means that fewer will be set up but that more samples will be taken from those that are established. The opposite trend will govern grab sampling where a site is relatively inexpensive to establish but where the proportional cost of a set of chemical measurements is higher. The contrast is well illustrated by the ratio of the cost of a set of chemical measurements to that of establishing a site. With automated sampling, it costs only 0.4-0.8 percent of the cost of establishing a site to obtain and analyze one set of measurements, while with grab sampling the figure is 53 percent. Comparison by the same ratio must be even more disproportionate with the measurement of flow, could the comparison be clearly defined. Thus it is clear that use of an automated sampler argues for taking many observations, once a site is established, but against the establishment of many sites, while use of grab sampling presents the opposite view.

We have attempted to list all costs, especially those of personnel and overhead. In trying to use our cost figures, anyone must make allowance for this fact. There sometimes seems to be a tendency for an agency to reason that once workers are employed and laboratories established, then the only costs are for field expenses and supplies. From this point of view, our costs will seem too high, or perhaps discourage investigation. In fact, however, many of the costs we list are already being paid by the agency.

Precision Attainable

The method used here to determine the rate at which proportional standard error decreases as the budget increases was to consider the same general sampling design over a range of budgets, each time assuming optimal allocation of effort within the constraints of the survey design. Results of such comparisons are shown in Table 15, and in Figures 7, 8, and 9 for some parameters.

These results apply conceptually to an entire river basin, even though derived from restricted parts of a basin, under the assumption that the variance components would not change in moving to the larger geographic unit. It is possible, of course, that the components for sites and for interaction of sites and periods in particular, might be greater if remote parts of a basin were included, but for discussion here we assume no such change.

A first conclusion is that the determinations of water quality parameters were of disappointingly poor precision. Exactly what constitutes useful precision is a matter of subjective, not statistical, judgement. Workers in some fields may feel uncomfortable about proportional standard errors greater than 0.05. For ecological studies I have sometimes offered the purely subjective personal judgement that a proportional standard error of 0.15 or less is probably useful administratively, though perhaps not in research. Even this permissive criterion is not met here by flow or yield of water, or by any determinations of transport or yield of chemicals, even at the highest budgets considered. Therefore, we may conclude, first, that while concentrations may be measurable with precision within usually accepted standards, it is likely that flow and the related measures of yield and transport may not be so measurable. Second, however, perhaps we must learn to use information of such poor precision, because probably it is the best we are going to have.

The relatively poor precision of these estimates arises from the inherent variability of the data; it is not a result of using probability sampling. Sampling by any other method will be subject to similar errors, although the imprecision may not be apprehended because it is not quantified. In contrast, when using probability sampling we can estimate the precision. Of course, it is quite possible that certain special plans of judgement sampling could be subject to less variability as, for example, if only moderate or high flows were to be measured, but then the universe under study could not be defined exactly.

A second conclusion is that precision increases more slowly with increased budget than should be expected, for example, with simple random sampling. With the latter, one may expect the proportional standard error to decrease as the reciprocal square root of the sampling effort. The budget is a good measure of sampling effort if adjusted for the constant (overhead) cost. In Table 15 changing from an available budget of $94,000 ($108,000 minus $14,000) to one of $225,000 ($269,000 minus $14,000) should reduce standard error (which must be calculated here as log [proportional standard error plus 1]) to about 61 percent of its value at the lower budget if the square root rule applied (and to 78 percent with a fourth root rule). Actually, all but one of the values at the higher budget ranged between 75 and 78 percent of those at the lower budget. The single exception and lowest value was for nitrate nitrogen at 64 percent, but this was a special case.

The reasons for departure from the square root rule are apparent in examining the basic relationship (Formula 2) and Figures 7, 8, and 9. The components of variance for sites and visits are most important in determining the precision, and these are divided by either number of sites or number of visits, but not by both. Any increase in budget must be spread over increases in both number of sites and number of visits; therefore neither can be increased in direct proportion to the budget (except in the special case so well represented by nitrate nitrogen in this study). The divisor for the variance component for error, in contrast, includes the product of number of sites and number of visits, and thus error follows the square root rule. But it is of little relative importance in determining the proportional standard error because its divisor is so large and its value decreases so rapidly with increased sampling.

The contributions made by the different components of variance are illustrated in Figures 7, 8, and 9. Each figure shows the value for the total variance (and proportional standard error) for both automated and grab samples over the range of budgets considered. The curve for automated sampling would be a straight line were it not for the effect of the overhead costs; in each figure its general slope approximately illustrates the square root rule because the number of sites is proportional to the available budget. With yield of water (Figure 7) and total phosphorus concentration (Figure 8) the line representing total variance of the estimate declines at a lesser rate reflecting the generally parallel course of contributions from sites and visits. The contribution from error declines at the rate expected under the square root rule. The interaction also seems to decline at this rate for the brief range of budgets for which it is visible on these graphs, but this appearance results from the fact that in all three graphs the number of sites increases in direct proportion to the available budget in this portion of the curve. This happens because at these lower budgets the number of visits (fixed here as the minimum number required to calculate a variance) already exceeds the calculated optimal value, therefore is not increased, allowing sites to increase in direct proportion to the budget.

This last effect also governs the special case of nitrate nitrogen (Figure 9). Here the requirement of 2 visits per period so far exceeds the optimal value that the contribution from the component for visits remains constant and relatively unimportant throughout the entire range of budgets considered. In consequence, the contribution from the component for sites declines throughout this range at the rate expected by the square root rule, and the total variance declines at a similar but decreasing rate.

This information on attainable precision and optimal allocation of effort (Table 15) is more important for guidance in future studies than as a postmortem of the one we have completed. The figures for optimal allocation at lower budget levels are suspect; the requirement of 2 visits per period (imposed so that a variance could be calculated) had the result that with the minimum number of 26 visits per year, only a few sites could be covered before exhausting the budget. At these lower budgets, the use of longer periods, fewer visits per site and more sites would have been better for all parameters except Kjeldahl nitrogen. The figures at the higher budget levels, however, better illustrate the differences among parameters with reference to optimal division of sampling effort among sites and visits. The greatest difference is between nitrate nitrogen with its high demand for number of sites and Kjeldahl nitrogen with its demand for number of visits.

Planning Other Studies

In designing a survey of another river basin, one would not have the information we have in retrospect with the Chowan. Further, even if one does have such information, the chances are that the optimal allocation of sampling effort for one variable may be inefficient for another (e.g., as here with nitrate nitrogen and Kjeldahl nitrogen). This is a common problem with surveys involving numerous variables, and compromise is required because almost never may a survey be based on a single variable.

One may design the survey to best suit the most important variable and let the rest be determined as may happen. Or, one may select some median status of variables and design a survey for this. In the study of water quality of a river basin of the type discussed here, the difficulty of obtaining any reasonable precision in the measurement of either flow or yield of water and the closely related values of transport and yield of the chemical constituents may urge that primary attention be given to the measurement of flow. It also happens that in this study flow and water yield occupy median positions as to optimal distribution of sampling effort. Determination of flow calls for a number of sites somewhat greater than the number of visits per year, but when the flow of each small basin is adjusted for its area, the balance shifts and the number of sites required is somewhat less than the number of visits.

As a rule of thumb, then, we propose that the number of sites be made approximately equal to the number of visits. If some variable where information is needed has unusually high spatial variability, then the balance may favor sites, and vice versa. There is no theoretical basis for this suggestion beyond the observation in this study that approximate equality of variance components holds a median position among the parameters investigated. The suggestion may well be discarded after further work, but for now it is suggested as a conservative plan.

Ordinarily, the best known dimension of a pending study is the budget. Rewriting formula (4), and setting s (number of sites) equal to pv (number of visits per year), the number of sites (or annual visits) may be calculated as:

$$(-c_s + (c_s^2 + 4c_v C)^{\frac{1}{2}})/2c_v$$

where C is the available budget. Substituting the values for costs observed here for grab sampling, this becomes:

$$-0.964 + (0.929 + 0.0126C)^{\frac{1}{2}}$$

This suggests about 13 sites visited 12 times per year for an available budget within $15,000 in 1975. This would break conveniently into 6 periods of about 2 months each, each with 2 visits per site. For an available budget of $100,000 in 1975, 35 sites should be used, with 34 visits to each; this would provide 17 time strata of about 21 days each.

Grab Sampling Compared with Automated Sampling

The basis of comparing grab sampling with automated was the attainable precision (expressed as proportional standard error) of estimates produced by each method under equal budget. Grab sampling was assumed to allocate the sampling effort in an optimal manner but within our sampling design, this constraint resulted in less than maximum efficiency at low budgets. Automated sampling was assumed to be on a fixed schedule of weekly service visits at which an average of 3.3 water samples would be retrieved; these samples were considered to be random in time. This fixed schedule also resulted in less than possible efficiency; in principle the schedule for an automated sampler might be changed within limits set by the design and capacity of the sampler and by sample storage problems. Thus the present comparison is strongly dependent upon these assumptions.

The comparison was made for the range of budgets previously considered, extended here to demonstrate that precision could actually be equal for the two methods if the budget were high enough. Otherwise, grab sampling resulted in greater precision than automated sampling for all cases examined, as may be noted in Table 16 and in greater detail in Figures 7, 8, and 9 for three of the parameters. The single exception was observed with measurement of yield of water where automated sampling was equally cost-effective at a very high budget and more efficient at even higher budgets. In all other cases, and especially at modest budgets, grab sampling was clearly more cost-effective.

This claim for superiority of grab sampling must, however, be clearly understood to be made on the limited basis of comparison of precision of determination of an average value under an equal budget, in a study limited to a single year. No weight is allowed for the other functions that an automated sampler can accomplish. For example, an automated sampler provides a continuous record of flow and allows study of the characteristics of different portions of the hydrograph during a runoff episode, a capability lacking in the instantaneous measurement provided by the grab sampling. Neither was any allowance made for salvage value of instrumentation or continued use of an automated site after the conclusion of a one-year study. But for the special comparison made here, grab sampling appears to provide generally better precision at equal cost.

The superiority of grab sampling in this comparison arises from its greater flexibility in covering numerous sites, and thus reducing the numerical importance of the variance component for sites as a contribution to the standard error. That is, it is easier to maximize information under a fixed budget by adjusting the balance between number of sites covered and annual visits per site.

Automated sampling, in contrast, is very effective in reducing variance due to temporal fluctuation; in fact, it entirely eliminates that component in the continuous recording of flow. But automated sampling costs so much per site added that it is impossible to reduce the effect of the spatial component very much under modest budgets and optimal allocation. The economics of automated sampling are such that once the instrument is established at a site, it can provide at relatively low cost numerous samples for chemical determinations, and measure flow continuously. These characteristics make the apparatus ideal for studying what happens at a single site. But the high cost of covering more sites prohibits any large spatial sample.

In fact, the ease with which more samples can be taken for chemical analysis may be misleading. Each of these samples must be analyzed chemically, and this adds to the cost of the study. A trial cost analysis on the basis of including the weekly service trips in the per-site costs and adjusting the number of water samples to be analyzed, with the option of more sites sampled, suggested that only with Kjeldahl nitrogen would anything approaching our average of 13 water samples per 4-week period be justified on the basis of precision; optimal strategy usually called for fewer analyses and more automated sampling sites. This last comparison is not really appropriate in our study because the stage-activated sampling schedule we used was designed for other purposes. But had the automated sampling schedule been designed primarily for better overall precision, the cost-effectiveness could have been improved somewhat, though probably not enough to match the grab sampling efficiency.

SECTION 5

ASSOCIATED WATER QUALITY INTERPRETATIONS

GRAB SAMPLING DATA AND ANALYSES

The field data necessary to evaluate the feasibility of statistical sampling have been analyzed to take advantage of this extensive information base in order to better understand the characteristics of rural runoff and areawide water quality. These analyses are summarized in sections that present (1) a data summary for each of the 15 statistical survey sites that include relationships between water quality and land use, (2) comparisons of unchannelized and channelized Coastal Plain stream water quality, (3) analysis of seasonal fluctuations, (4) concentration versus water yield, (5) comparison among geoclimatic areas,(6) a stream reach substudy, (7) comparison of study basin versus mainstream water quality, and (8) an overall basin data summary.

Two years of data (November 1974 to November 1976) were collected at the forested Piedmont (F); poorly-drained Coastal Plain (P) and well-drained Coastal Plain (W) sites; and 18 months (June 1975 to November 1976) of data were collected at the agricultural Piedmont (A) sites. The 18 months of compatible data from all sites were employed for most analyses so comparisons could be based upon a uniform time interval. The full two-year data set was employed, however, for analyses of seasonal variations. The data analyses fit into two broad classes which either relate site values to land-use activity or investigate differences in regional water quality.

Arithmetic concentration averages provide information about in-stream conditions. Volume average concentrations (flow weighted averages), however, provide information about the net water quality during a time interval and thus are meaningful to downstream receivers. Therefore, several sections provide dual analyses so that the data can be reviewed with respect to these two concepts.

SUBBASIN DATA SUMMARY

Prediction of present and future rural water quality is often based upon models which relate water quality to macro land-use factors. These models are probably best supported by a national water-quality land-use study of 928 sites reported by Omernik (1977). That study found increased nitrogen and phosphorus concentrations with increased agricultural intensity. Water-quality land-use relationships for the 15 statistical survey sites were investigated to determine if similar relationships were evident in this watershed. These analyses investigate both in-stream conditions and exported water quality as a function of percent forested area.

The land-use summary (Table 3) for these subbasins showed that the forested area, plus agricultural area, was approximately equal to the total subbasin area at each site. Thus, in these subbasins decreased forested area indicated increased human activity which was primarily agriculture. Therefore, major trends which are observed for water-quality constituents with respect to percent forested area would also exist (only inversely) with respect to percent agriculture.

Site water quality versus land-use relationships for COD, TP, TKN, and NO_3-N concentrations during June 1975 to November 1976 are presented in Figure 10. For each of the four parameters, the grab sampling mean, mean ± one standard deviation, maximum, and minimum values at each site are plotted as a function of percent forested area. From a water-quality perspective, the COD, TP, and TKN graphs indicate that no meaningful mean concentration increase occurred as the percent forested area decreased. Indeed, even the range of values for these parameters was relatively constant for all sites. The mean NO_3-N concentration also does not display a concentration increase with decreased forested area, but the range of values varied considerably from site to site which indicates that the sites were probably differentially impacted by the general land-use activities considered. The major conclusion obtained by examination of these graphs was that the mean time average concentration was relatively uniform throughout the watershed and did not increase as agricultural activity increased.

The effects of land use on receiver system water quality was assessed by analyzing flow weighted concentrations of COD, TP, TKN, and NO_3-N versus percent forested area for the 15 statistical survey sites during June 1975-November 1976. These data are displayed in Figure 11. The flow weighted concentrations do not present any clear relationship between water quality and percent forested area so regression models were not attempted.

It is both reasonable and often reported that nutrient levels in streams increase as agricultural intensity increases, but often a wide range of confidence limits exist for regression models developed for large geographic areas. For example, one regression model (Omernik, 1977) relating mean total phosphorus concentration to percent agriculture plus urban area for the eastern U.S. had broad confidence limits as measured by a ratio for the ± one sigma range to predicted mean value of 130 percent. The Chowan concentration versus land-use graphs point out the need for caution when employing model predictions to specific cases. Regression models employing macro land-use factors do not account for varying agricultural cropping patterns and management practices, annual weather conditions, stream border buffer systems or other factors which can impact agricultural effects on water quality.

While direct water-quality land-use relationships for the Chowan data were weak, differences related to geoclimatic area, season, and size were observed. These differences are the subject of the following sections.

CHANNELIZATION EFFECTS

The influence of subbasin soil type on stream parameter levels may have been confounded in the Coastal Plain region of this study by the impact of channelization. The Coastal Plain study areas were chosen on the basis of well- and poorly-drained soils. However, parts of both the well- and poorly-drained Coastal Plain have been channelized to expedite surface and subsurface drainage for greater agricultural flexibility and productivity. To illuminate possible channelization effects, the Coastal Plain sites were reclassified into unchannelized and channelized streams with four sites in each class. It should be noted that this study and that by Kuenzler et al. (1977) are not before and after channelization evaluations at given streams, so differences attributed to channelization may be confounded with or due to other factors.

A summary of the chemical and physical properties of the sampled unchannelized and channelized streams is presented in Table 17. An F-test was performed to determine whether the mean values for the two classes differed significantly considering the variation that was observed for the mean of each site within the two classes. The analysis showed that there was no evidence ($P>0.10$) of a difference in the mean TKN, NH_3-N and SS concentrations or the mean temperature and pH values between the channelized and unchannelized stream classes. However, because significant ($P<0.10$) differences were noted for the remaining parameters, the unchannelized stream values were employed as the standard in discussing possible effects of channelization.

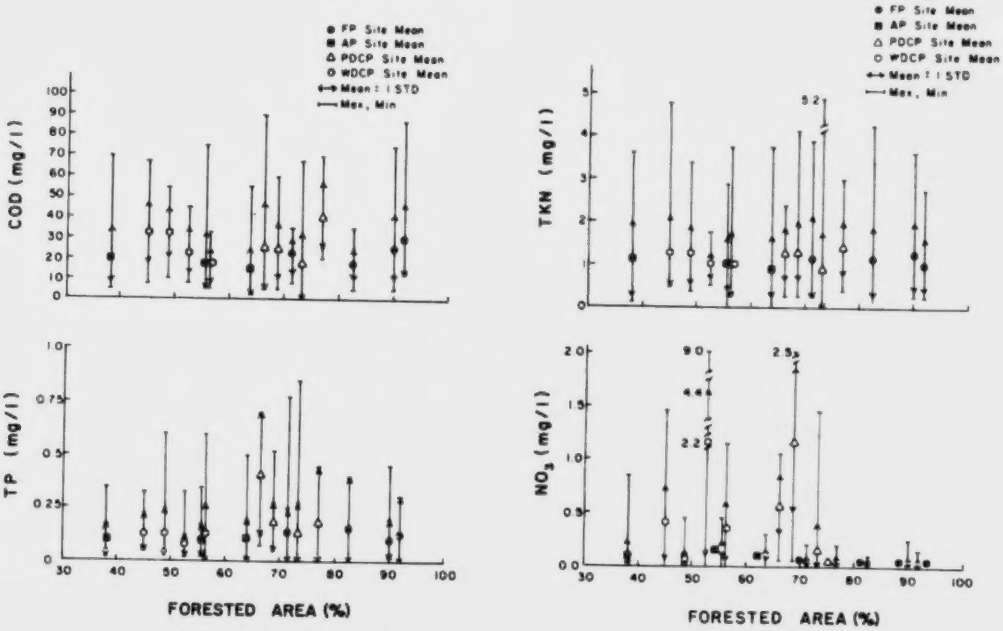

Figure 10. Site arithmetic data summary versus land use for grab sampling (June 1975 to November 1976).

The data showed that the average velocity and DO concentration were about 12 percent greater in the channelized streams than in the unchannelized streams. The channelized streams also had higher average TP (40 percent) and NO_3-N (380 percent) concentrations, but the average TOC and COD concentrations were about 15 percent lower. In a similar study, Kuenzler et al. (1977) also found that the mean annual nitrate concentrations for unchannelized streams (0.06-0.11 mg/l) was much less than for channelized streams (0.4-1.7 mg/l) for several rural streams in the North Carolina Coastal Plain. Thus, the influence of stream channelization appears to be the loss of natural swampy buffer strips in which plants can extract both nitrate and phosphate and where nitrate can also be lost through denitrification in the saturated soil layers. However, the swampy buffer strips results in increased organic inputs as measured by TOC and COD. The increased DO levels in the channelized streams probably reflect both the increased aeration association with increased water velocity and the lower oxygen demand of the less swampy type inputs.

SEASONAL FLUCTUATIONS

Earlier studies (Stanley and Hobbie, 1976) found that seasonal timing of nutrient concentrations and loads was important to the algal growth in the lower Chowan River so the rural runoff data were analyzed for seasonal trends. The seasonal fluctuations of water yields (WYD) and flow weighted concentrations from the four geoclimatic areas are presented in Figures 12

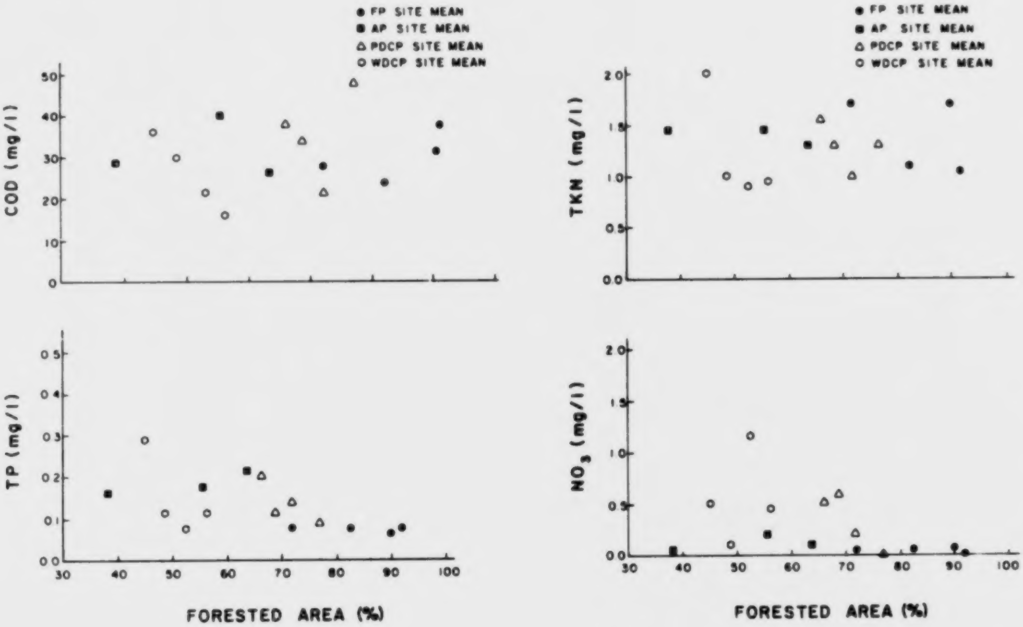

Figure 11. Site flow weighted concentrations versus land use for grab sampling (June 1975 to November 1976).

TABLE 17. CHANNELIZATION EFFECTS DATA SUMMARY, DECEMBER 1974-DECEMBER 1976

Variable	Units	N	Mean	Minimum value	Maximum value	C.V. %
			4 Unchannelized Streams			
COD	mg/l	116	31.0	4.0	71.0	47
TOC		115	13.4	1.0	36.0	54
TP		185	0.13	0.02	1.65	109
NH$_3$		48	0.12	<0.01	1.30	223
NO$_3$-N		186	0.24	<0.01	1.46	121
TKN		186	1.30	<0.04	11.1	83
Cl		185	7.54	1.50	51.4	57
SS		71	10.5	0.5	167.0	193
DO		181	7.37	0.20	14.2	41
VELOCITY	m/sec	192	0.10	0.0	0.57	114
pH		123	5.91	4.9	7.6	13
TEMP	°C	199	13.8	0.1	26.0	48
			4 Channelized Streams			
COD	mg/l	121	25.5	<4.0	91.0	61
TOC		122	11.3	<1.0	39.0	63
TP		197	0.18	0.02	1.36	106
NH$_3$		52	0.14	<0.01	1.15	198
NO$_3$-N		198	0.92	<0.01	8.96	142
TKN		198	1.20	<0.04	5.25	64
Cl		198	9.40	1.50	20.60	33
SS		77	13.3	0.56	75.0	103
DO		183	8.25	1.70	14.4	30
VELOCITY	m/sec	191	0.16	0.0	0.75	83
pH		121	6.02	4.80	7.20	8
TEMP	°C	198	14.5	2.0	26.0	43

and 13. Water yields tend to be higher in winter and spring, but relationships between area constituent concentrations in different geoclimatic areas and season were less well defined.

The concentration data do indicate two interesting relationships. The NO_3-N concentration graph shows that the Piedmont values were less than the Coastal Plain values for all recorded seasons and the TP concentrations in the agricultural Piedmont were comparable to the forested Piedmont values except for the summer of 1975.

Next, both land use and seasonal effects on water and nutrient yields from the 15 statistical survey watersheds were assessed by a model of the form:

$$Y = Y_s e^{-BF} \quad (1)$$

where Y is the yield; Y_s is a seasonal constant; B is an attenuation coefficient; and F is the percent forested area of the subbasin. A year was composed of four, 3-month seasons representing winter, spring, summer and fall, with winter corresponding to December, January, and February. The results of fitting WYD, TKN, NO_3-N and TP transport data (15 site means x 8 seasons)

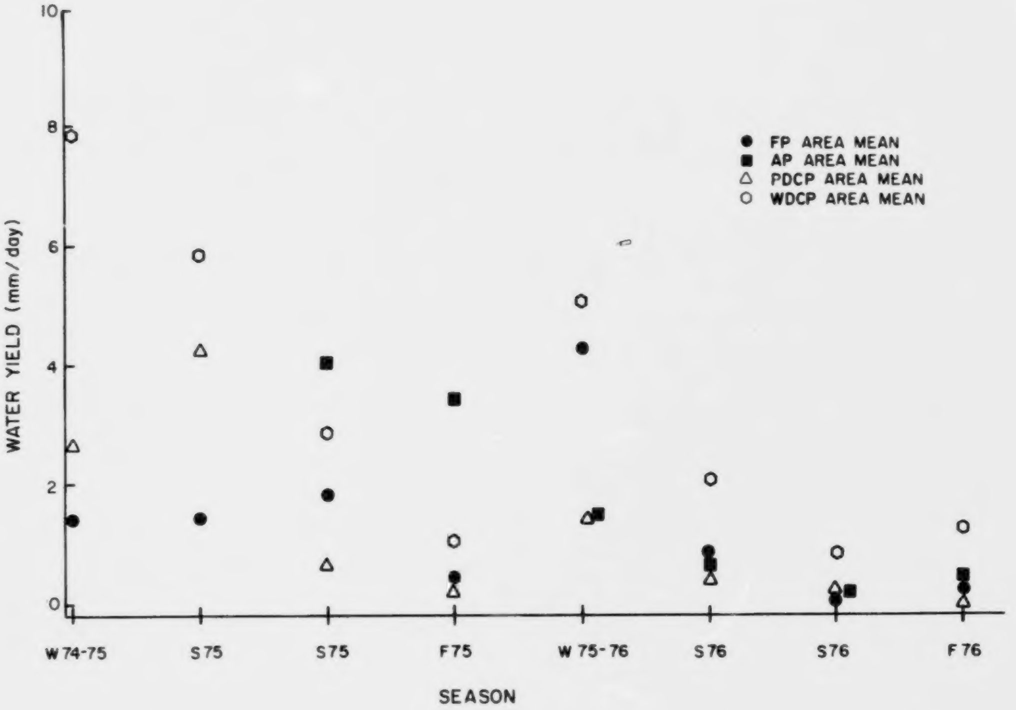

Figure 12. Areal seasonal water yield for grab sampling (November 1974 to November 1976).

to this model are summarized in Table 18. Analyses showed that the models were not appreciably improved by letting B vary with season. This analysis indicated that water yield was about 430 percent greater during the winter and spring seasons than during the summer and fall seasons. The nutrient yield models demonstrated relationships similar to the water yield model.

Finally, the land use and seasonal effects on flow weighted concentration were assessed by a model of the form:

$$C = C_s e^{-BF} \qquad (2)$$

where C is the concentration and C_S is a seasonal constant. The results of fitting TKN, NO_3-N and TP concentrations (15 site means x 8 seasons) to this model are summarized in Table 19. In general, the models displayed signifi- relationships but had lower r^2 values. With this model, TKN and TP concentration variations were attributable to seasonal but not land-use effects, while NO_3-N concentrations were a function of both season and land use. Again, the models were not appreciably improved by allowing B to vary with season.

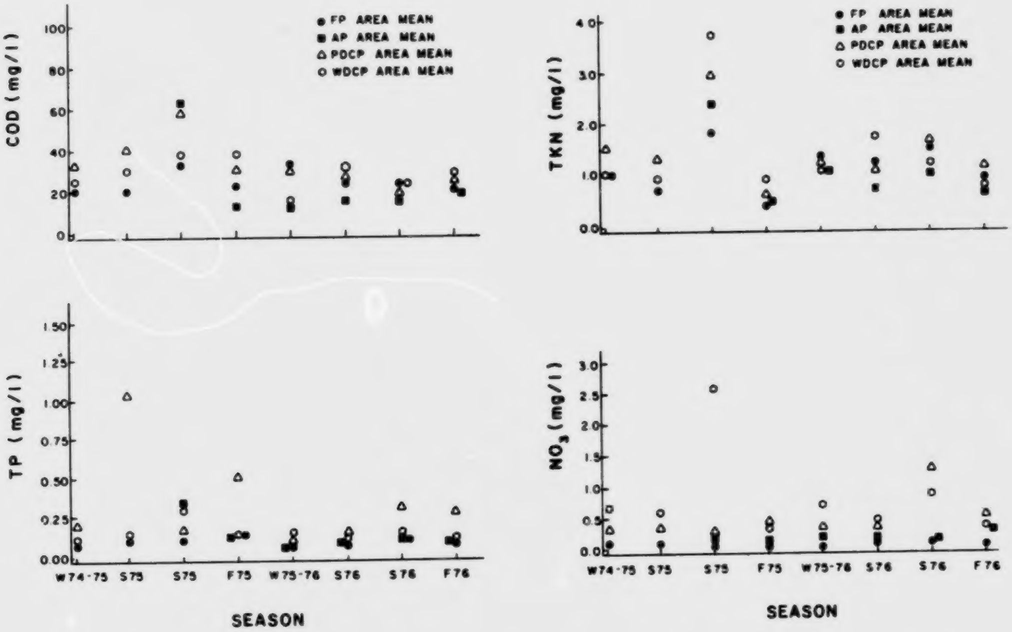

Figure 13. Aereal seasonal flow weighted concentrations for grab sampling (November 1974 to November 1976).

CONCENTRATION VERSUS WATER YIELD

Models of nonpoint source constituent transport typically employ a hydrologic model for the main program and assume some empirical relationship between flow rate and constitute concentration to calculate constituent loads. The rural runoff nutrient data were employed to investigate possible relationships between concentration levels and water yield values to assist in model development for the Chowan watershed.

TABLE 18. CONSTITUENT YIELD MODELS INCORPORATING LAND USE AND SEASON

Variable	Season	Y_s	B	r^2	Land Use	Season
WYD (mm/day)	Winter	1.20±0.14	0.0235	0.52	$P<0.01$**	$P<0.01$**
	Spring	0.87±0.58	0.0235			
	Summer	0.23±0.18	0.0235			
	Fall	0.16±0.05	0.0235			
TKN ($kg/km^2 \cdot DAY$)	Winter	97±9	0.0248	0.53	$P<0.01$**	$P<0.01$**
	Spring	57±34	0.0248			
	Summer	29±24	0.0248			
	Fall	8±1	0.0248			
NO_3-N ($kg/km^2 \cdot DAY$)	Winter	236±56	0.0667	0.51	$P<0.01$**	$P<0.01$**
	Spring	190±151	0.0667			
	Summer	35±23	0.0667			
	Fall	12±6	0.0667			
TP ($kg/km^2 \cdot DAY$)	Winter	11±3	0.0288	0.48	$P<0.01$**	$P<0.01$**
	Spring	16±14	0.0288			
	Summer	3±2	0.0288			
	Fall	2±1	0.0288			

Model: $Y = Y_s e^{-BF}$

**Highly Significant

TABLE 19. CONSTITUENT FLOW WEIGHTED AVERAGE CONCENTRATION MODELS INCORPORATING LAND USE AND SEASON

Variable	Season	C_s	B	r^2	Land use	Season
TKN (mg/l)	Winter	1.20±0.02	0.0013	0.44	$P>0.10$	$P<0.01$**
	Spring	1.05±0.12	0.0013			
	Summer	1.65±0.26	0.0013			
	Fall	0.78±0.15	0.0013			
NO_3-N (mg/l)	Winter	2.88±0.36	0.0432	0.30	$P<0.01$**	$P<0.05$*
	Spring	2.72±0.78	0.0432			
	Summer	2.76±0.64	0.0432			
	Fall	1.08±0.28	0.0432			
TP (mg/l)	Winter	0.135±0.017	0.0052	0.20	$P>0.10$	$P<0.01$**
	Spring	0.208±0.096	0.0052			
	Summer	0.194±0.010	0.0052			
	Fall	0.196±0.036	0.0052			

Model: $C = C_s e^{-BF}$

*Significant

**Highly Significant

For the purpose of this discussion, water yield (mm/day) refers to individual flow measurements divided by the appropriate subbasin area. These values need to be distinguished from annual average water yield (mm/yr) values which are computed from several water yield (mm/day) values. Water yield values were employed rather than flow rates to allow direct comparisons among sites.

Plots of COD, NO_3-N and TP concentrations versus water yield are generated for each site. Because a review of these graphs indicated little or no consistent relationship between the parametic concentrations and the water yield, no empirical relationships with general application to all sites were generated. However, reviewing the data did produce some qualitative relationships which are helpful for related 208 type activities.

The NO_3-N data showed that the five highest concentration measurements, which were all greater than 5 mg/l, were all obtained in the well-drained Coastal Plain at the W-4 subbasin. The NO_3-N graph in Figure 10 shows the high level of these values relative to those at other sites. W-4 was the smallest watershed with an area of only 0.5 km^2 (0.2 mi^2) and the next larger watershed was almost 10 times as large. The W-4 stream channel was well defined and extended into the cropped fields of the watershed. The NO_3-N concentration at W-4 increased with decreasing water yield as shown in Figure 14. Four of the elevated NO_3-N measurements were made at low water yield conditions during the period of June to September 1976, and the fifth measurement during a low water yield condition in August 1975. Animal production had not been observed during site inspections; and data also indicated there was no relationship between either COD, TP, or Cl concentration and flow at this site, so the increased NO_3-N concentrations were not attributable to animal waste.

In plot studies of nitrogen losses from row crops in well-drained soils of the North Carolina Coastal Plain, Gambrell and Fisher (1966) measured nearly constant nitrate concentrations of about 15 mg/l from subsurface drainage. Because the W-4 watershed was approximately 50 percent agriculture and 50 percent forested and the nitrate nitrogen concentrations during low flow conditions were 6-7 mg/l, it appears that these high values resulted from the subsurface drainage of the agricultural land. Although the other three WDCP subbasins had similar land use, these subbasins were 15 to 30 times larger than W-4, and the maximum NO_3-N concentrations at these sites were all less than 2.5 mg/l. It was hypothesized that in-stream processes were responsible for the reduction in NO_3-N concentration at these sites.

In summary, measured concentrations did not display any consistent functional relationship to water yield levels. However, data from Gambrell and Fisher (1966) and this study showed that NO_3-N concentrations at small (<0.5 km^2) well-drained Coastal Plain sites were elevated during low flow conditions during the summer; however, elevated NO_3-N concentrations were not observed at sites draining 10 km^2 (2.6 mi^2) watersheds.

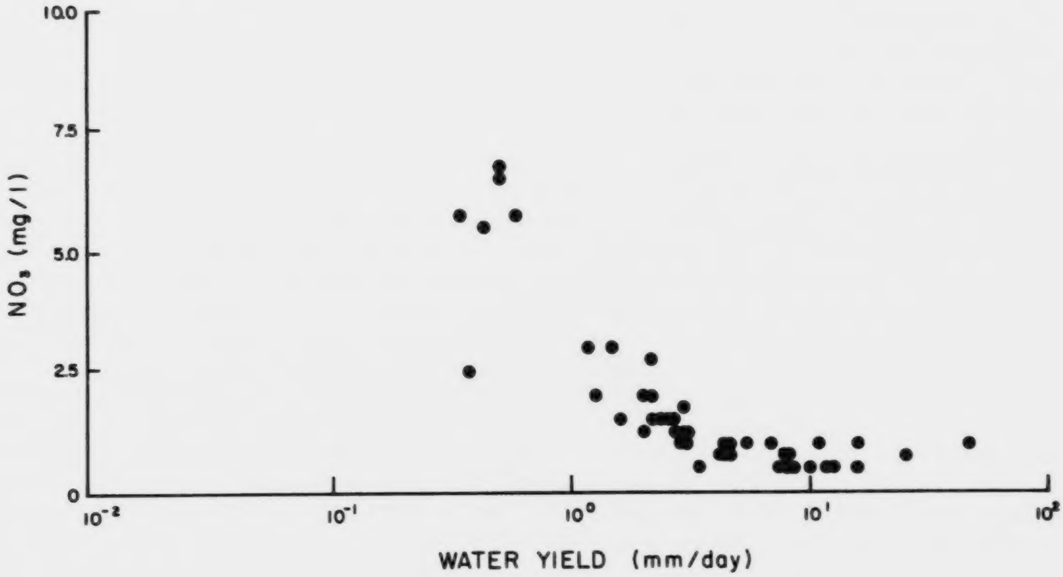

Figure 14. NO_3-N versus water yield at a small (0.5 km^2) well-drained Coastal Plain site for grab sampling (November 1974 to November 1976).

COMPARISONS AMONG AREAS

The purpose of this section is to investigate possible differences between geoclimatic areas based upon site average values. Analyses are presented for both in-stream (arithmetic average) and export (flow weighted average) summaries.

Arithmetic Average Concentrations

Stream conditions for the 15 statistical survey streams are summarized by geoclimatic areas in Table 20. The 15 statistical survey site mean values were employed to evaluate possible physical and chemical differences between streams in the Piedmont and Coastal Plain, agricultural Piedmont and forested Piedmont, poorly-drained Coastal Plain and well-drained Coastal Plain. These comparisons were performed by an analysis of variance using log-transformed data, and the results are summarized in Table 21.

The analysis of variance indicated a significant ($P<0.10$) difference between the well-drained Coastal Plain and poorly-drained Coastal Plain water yield (WYD) values. The WYD data indicated that the mean WYD from the W sites was about five times as great than from the P sites and that the WYD variation within the W sites was relatively large. The elevated water yield value of the W sites was primarily due to the measurement of high water yields at two of the four sites. At one of these sites, a relatively infrequent, very high flow event resulted in the elevated mean value. At the second site, the high mean value was attributable to numerous moderate water yield measurements which may reflect groundwater input from areas outside of the basin surface drainage area. Due to the proximity of the W and P sites, it was reasonable to assume that rainfall amounts were similar during the 18-month study period and that the difference in mean water yields was a data set artifact. However, because the water yield difference was 400 percent, it had a major impact on nutrient yield comparisons among the four study areas.

The analysis of variance also showed significant ($P<0.10$) differences existed among geoclimatic areas for some of the other physical and chemical parameters. The mean water velocity was approximately 100 percent greater in the Piedmont than in the Coastal Plain. Although temperature differences were established between both the Piedmont versus Coastal Plain and the poorly-drained Coastal Plain versus well-drained Coastal Plain areas, they were not considered meaningful on a general water quality basis because the variations were less than 5 percent. Thus, the 25 percent greater dissolved oxygen level in the Piedmont compared to the Coastal Plain probably reflected increased aeration associated with high velocities in the Piedmont streams. The lower conductivity (COND) level (28 percent) and chloride concentration (45 percent) in the Piedmont compared to the Coastal Plain probably were due to decreased atmospheric inputs with increasing distance from the ocean as recorded in precipitation studies by Gambell and Fisher (1966).

The average in-stream NO_3-N concentration of the Piedmont streams (0.07 mg/l) was substantially less than the Coastal Plain value (0.64 mg/l). However, the NO_3-N analysis of variance model had a smaller r^2 (0.25) because the

TABLE 20. ARITHMETIC DATA SUMMARY FOR GRAB SAMPLING, JUNE 1975-NOVEMBER 1976

Variable	Units	Mean of sites	Minimum site average	Maximum site average	C.V. %	Variable	Units	Mean of sites	Minimum site average	Maximum site average	C.V. %
Forested Piedmont - 4 Sites						Well-Drained Coastal Plain - 4 Sites					
WYD	mm/day	1.28	0.85	1.5	23	WYD	mm/day	2.18	0.48	3.77	84
VELOCITY	m/sec	0.20	0.17	0.29	30	VELOCITY	m/sec	0.07	0.05	0.09	29
TEMP	°C	14.5	14.2	14.7	1	TEMP	°C	14.9	14.5	15.3	2
DO	mg/l	8.56	8.40	8.81	2	DO	mg/l	7.00	5.87	7.87	13
pH		6.14	5.99	6.22	2	pH		5.93	5.61	6.08	4
COND	μmhos/cm	49.7	45.4	56.1	10	COND	μmhos/cm	60.1	54.5	63.0	6
Cl		5.46	4.23	6.93	21	Cl		8.25	6.36	9.88	18
COD		23.5	17.1	29.8	23	COD		26.1	16.9	32.6	28
TOC		8.78	6.74	10.5	18	TOC		10.5	7.3	13.3	27
TP	mg/l	0.12	0.10	0.14	17	TP	mg/l	0.12	0.07	0.14	25
NO_3-N		0.04	0.02	0.06	50	NO_3-N		0.75	0.06	2.20	131
TKN		1.12	1.02	1.19	6	TKN		1.10	0.94	1.28	15
SS		8.87	6.15	12.1	21	SS		8.7	3.5	18.4	75
Agricultural Piedmont - 3 Sites						Poorly-Drained Coastal Plain - 4 Sites					
WYD	mm/day	1.58	1.32	1.75	15	WYD	mm/day	0.43	0.30	0.52	23
VELOCITY	m/sec	0.17	0.13	0.20	24	VELOCITY	m/sec	0.11	0.06	0.13	27
TEMP	°C	14.9	14.5	15.7	4	TEMP	°C	15.6	14.8	16.2	4
DO	mg/l	9.08	8.93	9.21	2	DO	mg/l	7.13	5.56	8.38	19
pH		6.27	6.17	6.37	2	pH		6.01	5.82	6.07	2
COND	μmhos/cm	51.2	42.2	68.0	29	COND	μmhos/cm	80.4	67.8	89.5	14
Cl		4.20	3.51	5.08	19	Cl		9.37	7.19	11.36	18
COD		17.8	13.9	20.7	20	COD		26.6	16.8	40.5	37
TOC		6.98	6.05	8.32	17	TOC		10.7	7.6	18.3	46
TP	mg/l	0.10	0.10	0.11	4	TP	mg/l	0.22	0.13	0.41	59
NO_3-N		0.11	0.08	0.17	45	NO_3-N		0.53	0.03	1.17	108
TKN		1.00	0.92	1.13	11	TKN		1.18	0.84	1.33	19
SS		6.82	4.26	11.0	54	SS		14.4	6.9	28.0	67

Coastal Plain streams had a large inherent variation in mean concentrations (0.03 to 2.20 mg/l). The mean TP concentration in the poorly-drained Coastal Plain was about twice the value of 0.12 mg/l recorded for the well-drained Coastal Plain. The COD, TOC, TKN, and SS concentrations did not show any significant ($P<0.10$) variation among the four geoclimatic areas.

Flow Weighted Concentrations

Flow weighted concentrations for the statistical survey sites are summarized in Table 22. This table presents a data summary for water exported from the four geoclimatic areas as determined from the 18-month volume average concentration from each site within an area. These flow weighted concentrations for the 15 statistical survey sites were employed to evaluate

TABLE 21. ANALYSIS OF AVERAGE STREAM CONDITIONS FOR GRAB SAMPLING JUNE 1975-NOVEMBER 1976

		Probability of Significant Difference		
Variable	Model r^2	Piedmont vs. Coastal Plain	AP vs. FP	PDCP vs. WDCP
WYD	0.37	$P>0.10$	$P>0.10$	$0.01<P<0.05$*
VELOCITY	0.70	$P<0.01$**	$P>0.10$	$P>0.10$
TEMP	0.49	$0.05<P<0.10$	$P>0.10$	$0.05<P<0.10$
DO	0.59	$P<0.01$**	$P>0.10$	$P>0.10$
pH	0.54	$P<0.01$**	$P>0.10$	$P>0.10$
COND	0.71	$P<0.01$**	$P>0.10$	$P>0.10$
Cl	0.75	$P<0.01$**	$P>0.10$	$P>0.10$
COD	0.23	$P>0.10$	$P>0.10$	$P>0.10$
TOC	0.24	$P>0.10$	$P>0.10$	$P>0.10$
TP	0.40	$P>0.10$	$P>0.10$	$0.05<P<0.10$
NO_3-N	0.25	$0.05<P<0.10$	$P>0.10$	$P>0.10$
TKN	0.17	$P>0.10$	$P>0.10$	$P>0.10$
SS	0.19	$P>0.10$	$P>0.10$	$P>0.10$

*Significant Difference
**Highly Significant Difference

TABLE 22. FLOW WEIGHTED CONCENTRATION SUMMARY FOR GRAB SAMPLING DATA - JUNE 1975 TO NOVEMBER 1976

Variable	Mean of sites	Minimum site value	Maximum site value	C.V.
	---------	mg/l	----------	%
Forested Piedmont - 4 Sites				
COD	30.1	24.1	38.1	20
TOC	11.9	9.2	15.2	21
TP	0.072	0.068	0.073	6
NO_3-N	0.032	0.019	0.044	31
TKN	1.40	1.06	1.71	25
Cl	3.94	3.32	4.90	18
Agricultural Piedmont - 3 Sites				
COD	32.0	26.2	40.6	24
TOC	14.1	13.8	14.2	1
TP	0.184	0.163	0.171	16
NO_3-N	0.124	0.054	0.224	72
TKN	1.38	1.28	1.44	7
Cl	3.58	3.48	3.63	3
Well-Drained Coastal Plain - 4 Sites				
COD	25.8	16.3	30.2	34
TOC	10.1	6.1	15.4	40
TP	0.147	0.074	0.283	63
NO_3-N	0.556	0.098	1.174	81
TKN	1.21	0.92	1.99	43
Cl	7.13	4.85	9.03	25
Poorly-Drained Coastal Plain - 4 Sites				
COD	34.9	21.6	47.7	31
TOC	15.4	12.7	23.4	42
TP	0.134	0.090	0.195	34
NO_3-N	0.352	0.025	0.694	85
TKN	1.28	1.0	1.54	17
Cl	6.48	4.47	7.49	21

possible differences between geoclimatic areas. The comparisons were performed by an analysis of variance and the results are summarized in Table 23. No differences ($P<0.10$) were observed for volume average COD, TOC, and TKN concentrations among the study areas. For the 15 statistical survey sites, the average flow weighted COD, TOC, and TKN concentrations (30, 13, and 1.3 mg/l, respectively) were the same magnitude as the arithmetic average stream values (24, 13 and 1.1 mg/l, respectively) indicating that concentrations were relatively uncorrelated with respect to flow.

Significant ($P<0.10$) differences were noted between Piedmont and Coastal Plain NO_3-N and Cl concentrations. The flow weighted average NO_3-N concentrations were much lower in the Piedmont (0.08 mg/l) than in the Coastal Plain (0.45 mg/l). Likewise, the Cl concentrations were about 55 percent lower in the Piedmont than in the Coastal Plain. Finally, the analysis of variance indicated that there was a difference between the agricultural Piedmont TP concentration value of 0.18 mg/l and the forested Piedmont value of 0.07 mg/l.

In summary, analyses of variance employing 18-month arithmetic average and flow weighted average concentrations for the 15 statistical survey sites in four geoclimatic areas indicated that the dominant variation was between the Piedmont and Coastal Plain with relatively minor variation occurring between (1) the agricultural Piedmont and forested Piedmont and (2) the poorly-drained and well-drained Coastal Plain. The water quality differences between the Piedmont and Coastal Plain were judged to be primarily the result of naturally occurring physiographic variations in (1) basin characteristics, such as vegetation, soil type, stream hydraulics; and (2) ocean proximity.

TABLE 23. ANALYSES OF FLOW WEIGHTED AVERAGE CONCENTRATIONS FOR GRAB SAMPLING DATA, JUNE 1975-NOVEMBER 1976

		Probability of Significant Difference		
Variable	Model r^2	Piedmont vs. Coastal Plain	AP vs. FP	PDCP vs. WDCP
COD	0.18	$P>0.10$	$P>0.10$	$P>0.10$
TOC	0.25	$P>0.10$	$P>0.10$	$P>0.10$
TKN	0.06	$P>0.10$	$P>0.10$	$P>0.10$
NO_3-N	0.42	$0.05<P<0.10$	$P>0.10$	$P>0.10$
TP	0.41	$P>0.10$	$0.05<P<0.10$	$P>0.10$
Cl	0.68	$P<0.01$**	$P>0.10$	$P>0.10$

**Highly Significant

POINT SOURCE IMPACT

A substudy of a 32-km (20-mi) stream reach, shown schematically in Figure 6, was conducted for a 15-month period (12/19/75 to 3/12/77). This system was viewed as a model from which inferences as to the water quality impacts of various land uses and urban influences could be drawn. Thus, this substudy is separate and different from the statistically-based main study.

Arithmetic sample averages for this 32-km (20-mi) stream reach showed variations which seem related to inputs from point sources and swampy areas (Table 24). The COD and TOC appeared to be increased as a result of effluent input from a 1,200 person septic tank system (Site 2), a secondary treatment plant (Site 4), and a swamp (Site 5). The recovery zones (Sites 3 and 7) were physically different because Site 3 was channelized and Site 7 was heavily influenced by swampy inputs. Therefore, COD and TOC concentrations after the Site 2 input returned closer to background levels than after the downstream effluent (Site 4) and swamp inputs (Site 5). Total nitrogen increased as a result of effluent discharges (Sites 2 and 4) but decreased after the swamp input (Site 5) because swamp waters had a low nitrogen content. It was interesting that while ammonia variations were large, especially after the effluent input from secondary treatment (Site 4), that changes in both nitrate and total organic nitrogen (ON) (calculated using average TKN minus ammonia) were less than might have been expected throughout the total reach.

Total organic nitrogen values were probably impacted by the relationship between nitrogen inputs and incorporation to stream biomass. While the sample size was too small, the relatively high total organic nitrogen value at the last confluence (Site 6) may have been related to the large upstream reduction of ammonia. Ammonia is the nitrogen form most easily assimilated biologically and thus converted to organic nitrogen. Phosphorus concentrations were increased after both point source inputs but declined in the recovery reaches. Suspended solids were not markedly increased as a result of the first point source input (Site 2) because of the long stream reach prior to confluence, but at times appeared higher as a result of the second point source input and then decreased to a very low value at the last site compared to Site 4. This final decrease in suspended solids from Site 4 to Site 7, as well as phosphorus and total organic nitrogen concentrations, may have been due to settling in this slow, meandering stream reach.

In overview, the studied stream reach had high assimilatory capacity until inputs from point sources and swampy areas overrode this dynamic capability. It was noteworthy that concentrations in the background zones and the first recovery zone were very similar for most parameters (TP and NO_3-N were slightly higher). However, concentrations after the second point source and swamp input remained higher than in the background reach for all parameters but NH_3-N and ON. It was also interesting that the swamp input, while exhibiting high COD and TOC levels, actually resulted in reduced total nitrogen and total phosphorus values because of the dilutional effects of these very low nitrogen and phosphorus water and coincident settling that occurred in this slow moving stream. Therefore, for this stream reach major inputs of nitrogen and phosphorus, which appeared to come from treatment plant effluents, were reduced

TABLE 24. MEAN VALUES OF STREAM REACH SUBSTUDY

Constituent in mg/l	Samples	Sites						
		Head-waters 1	First Point Source Input 2	Recovery Reach 3	Second Point Source Input 4	Swamp Input 5	Conflu-ence 6	5 km Downstream 7
COD	17	21.2	28.8	23.7	26.6	33.4	27.4	32.3
TOC	17	6.6	8.0	7.2	8.8	13.2	9.6	10.2
TP	27	0.13	0.40	0.21	0.82	0.19	0.78	0.48
NH -N	5	0.05	0.16	0.04	1.47	0.05	0.08	0.14
ON	5	1.00	1.22	1.03	1.01	1.16	1.38	1.15
TKN	27	1.05	1.38	1.07	2.48	1.21	2.18	1.29
NO -N	27	0.26	0.57	0.49	0.56	0.03	0.49	0.52
TN	27	1.31	1.95	1.57	3.04	1.24	2.68	1.82
Cl	27	8.56	9.66	9.06	11.17	6.92	12.25	11.28
SS	10	12.9	12.6	11.2	18.8	5.4	11.3	4.3

to near background levels as long as the stream assimilatory capacity was not overwhelmed. Moreover, differing natural inputs because of changed physiographic factors may cause changes in water quality, such as possible differences in COC and TOC, due to swamp inputs as in this study. However, phosphorus and nitrogen species concentrations, except nitrate, evidenced real but small differences when contrasting the background reach (Site 1) and swamp input (Site 5).

These stream reach results suggested that nonpoint sources establish background water quality and that during nonrunoff conditions, point sources caused concentration increases that may or may not be reduced to headwater background levels, depending upon impact and recovery zone capabilities, as well as relative location along the stream reach. For example, concentration values at recovery Site 3 after the point source input (Site 2) were very similar to background Site 1 for most parameters (TP and NO_3-N slightly higher). However, the second point source, along with naturally occurring swamp inputs began to establish a different water quality at Site 7 as compared to Site 1; i.e., higher organics and oxygen demand, and elevated nitrogen and phosphorus levels.

HEADWATER VERSUS MAINSTREAM

To gain additional insight as to the relative water quality in headwater or rural areas and the main stream of the Chowan River system, initial comparisons were made using project data and information obtained from a compatible study in the lower Chowan (G. Cook, Personal Communication, North Carolina Department of Natural & Economic Resources, Raleigh, North Carolina, 1976). Because constituent concentrations in the small study basins and main stream draining these sites appeared to be similar, samples were taken at main stream locations receiving drainage from the statistical survey sites and the related survey sites on the same day. Comparison of average concentration values for these headwater and main river regions are shown in Table 25. These overall averages were based upon one main stream value and the average of one to three statistical site values for each sampling date. This data verified that water quality is very similar in the rural headwaters and the main river draining these rural areas based upon measured constituent concentrations. However, there were differences between regions indicating that in these predominantly rural study areas, main stream water quality reflects inputs from rural nonpoint sources and that these inputs or background conditions differ with geoclimatic regions.

General Basin Summary

The physical and chemical grab sample measurements for the 18-month statistical survey are summarized by geoclimatic areas in Table 26. Mean values for the four areas were relatively uniform throughout the river basin. However, the coefficient of variation (CV), standard deviation divided by mean, was typically greater than 30 percent for all measured parameters except pH which was typically about 8 percent. In many cases the CV approached 100 percent which indicated enormous naturally occurring variations within each geoclimatic area due to spatial, temporal, and random factors and demonstrated the large variation in individual sample values.

In order to evaluate overall rural nonpoint source impact, watershed mean concentration values were calculated and compared to water quality criteria proposed by the Environmental Protection Agency (EPA) and also typical values for secondary treated municipal wastewater as listed by Rubin et al. (1978). The 50 states have adopted individual receiving water quality criteria based upon EPA guidelines and local natural or background conditions. Although the North Carolina and Virginia regulations are somewhat different than the EPA guidelines, the EPA values are used for the following discussion of rural stream water quality. These values are presented only to provide a range of source and quality values for comparative purposes.

Dissolved oxygen (DO) is necessary to maintain fish and other aquatic life, so oxygen supply was measured as DO concentration and the potential for oxygen demand was assessed by TOC and COD concentrations. The mean DO levels of the four geoclimatic areas of the Chowan Basin were greater than the proposed minimum level of 5 mg/l; however, infrequent violations were measured. These violations usually occurred during low flow conditions in the warmer months. The watershed average TOC and COD concentrations were about 10 and 25 mg/l respectively, while the maximum recorded concentrations were about 40 and 90 mg/l, respectively. The COD concentration was typically about 2.5 times as great as the TOC concentration; this indicates a relatively oxidized state. Although EPA has not established water quality criteria for either TOC or COD, typical COD concentrations for raw and secondary treated municipal wastewater are 450 and 50 mg/l, respectively.

Nitrogen and phosphorus are basic elements for primary productivity and thus relative concentrations are often employed to assess the potential for algal production. Additionally, EPA has proposed a drinking water quality criterion for nitrate based upon human health considerations and suggested an upper limit of 10 mg/l as N. While the maximum measured NO_3-N concentration (9.0 mg/l) of the rural stream water approached this limit, almost all samples had concentrations much less than the proposed standard. For the study geoclimatic areas, the mean TKN and NO_3-N concentrations were approxi-

TABLE 25. COMPARISON OF HEADWATER AND MAIN RIVER CONCENTRATIONS

	Visits	COD	TOC	TN	NH_3-N	TKN	NO_3-N	Cl
		mg/l						
F-Sites	26	19.2	6.7	0.10	0.02	0.85	0.02	3.9
Meherrin River (Below F-Sites)	26	19.4	7.6	0.10	0.04	0.64	0.05	5.3
P-Sites	25	35.3	14.6	0.24	0.06	0.98	0.06	9.3
Chowan River (Below P-Sites)	25	32.8	13.6	0.24	0.06	0.85	0.06	13.0

TABLE 26. STATISTICAL SURVEY MEASUREMENT SUMMARY FOR GRAB SAMPLING, JUNE 1975-NOVEMBER 1976

Variable	Units	Number of Samples	Mean	Minimum Value	Maximum Value	C.V.* %	Variable	Units	Number of Samples	Mean	Minimum Value	Maximum Value	C.V.* %
		Forested Piedmont							Well-Drained Coastal Plain				
WYD	mm/day	144	1.28	0.0	31.1	280	WYD	mm/day	140	2.18	0.0	75.6	340
VELOCITY	m/sec	144	0.20	0.0	0.85	85	VELOCITY	m/sec	140	0.07	0.0	0.56	114
TEMP	^{o}C	144	14.5	1.5	24.0	39	TEMP	^{o}C	140	14.9	0.05	26.0	44
DO	mg/l	142	8.56	1.70	13.9	30	DO	mg/l	129	7.00	1.40	13.6	35
pH		70	6.14	5.00	7.20	8	pH		67	5.93	4.80	7.40	11
COND	µmhos/cm	144	49.7	10.0	110	38	COND	µmhos/cm	140	60.1	25.0	190	45
Cl		144	5.46	1.50	55.3	109	Cl		140	8.25	2.44	51.4	58
COD		72	23.5	<4.0	87.0	59	COD		70	26.1	<4.00	68.0	52
TOC		72	8.78	<1.0	30.0	65	TOC		70	10.5	<1.00	33.0	59
TP	mg/l	144	0.12	0.02	1.15	150	TP	mg/l	140	0.12	0.02	0.60	83
NO_3-N		144	0.04	<0.01	0.24	100	NO_3-N		140	0.75	<0.01	8.96	187
TKN		144	1.12	0.11	4.19	74	TKN		140	1.10	0.30	4.77	62
NH_3-N		50	0.03	<0.01	0.29	167	NH_3-N		41	0.07	<0.01	1.03	245
SS		74	8.87	0.33	94.3	182	SS		56	8.68	0.55	167	260
		Agricultural Piedmont							Poorly-Drained Coastal Plain				
WYD	mm/day	112	1.58	0.0	34.1	278	WYD	mm/day	136	0.43	0.0	7.62	44
VELOCITY	m/sec	112	0.17	0.0	1.11	106	VELOCITY	m/sec	136	0.11	0.0	0.50	82
TEMP	^{o}C	112	14.9	1.0	26.0	42	TEMP	^{o}C	136	15.6	2.0	26.0	41
DO	mg/l	105	9.08	5.50	13.6	24	DO	mg/l	136	7.13	0.20	13.1	38
pH		55	6.26	4.80	7.60	8	pH		71	6.01	4.70	7.60	10
COND	µmhos/cm	114	51.2	19.0	220	50	COND	µmhos/cm	136	80.4	1.30	300	50
Cl		112	4.20	2.10	29.3	73	Cl		136	9.37	2.63	20.6	31
COD		56	17.8	<4.0	75.0	76	COD		68	26.6	<4.0	91.0	71
TOC		56	6.98	<1.0	31.0	84	TOC		68	10.7	<1.0	36.0	77
TP	mg/l	112	0.10	0.02	0.50	80	TP	mg/l	136	0.22	0.03	1.65	109
NO_3-N		112	0.11	<0.01	0.87	100	NO_3-N		136	0.53	<0.01	1.69	158
TKN		112	1.00	<0.04	3.73	77	TKN		136	1.18	<0.04	5.25	62
NH_3-N		42	0.02	<0.01	0.14	200	NH_3-N		68	0.17	<0.01	1.30	188
SS		53	6.82	0.33	30.2	98	SS		68	14.4	0.8	75.0	97

*C.V. = Standard Deviation/Mean

mately 1.2 and 0.3 mg/l, respectively, so the average total nitrogen concentration was about 1.5 mg/l. Secondary treated municipal wastewater typically has a total nitrogen concentration of 25 mg/l which is approximately 10 times as great as the rural nonpoint source value.

To prevent biological nuisances, EPA suggested water quality criteria for TP is 0.1 mg/l for flowing streams not discharging directly to lakes or impoundments, 0.05 mg/l in any stream at the point where it enters a lake or reservoir, and 0.025 mg/l within a lake or reservoir. Because all four geoclimatic areas of the Chowan Basin including the forested Piedmont had a mean TP concentration greater than 0.1 mg/l, the natural or background phosphorus level in the Chowan Basin exceeded the suggested water quality criteria. Nevertheless, it should be noted that the rural nonpoint source maximum TP concentration (1.5 mg/l) was only about one-tenth the average TP concentration of 10 mg/l for secondary treated municipal wastewater.

The mean Cl concentration for the rural runoff was 6.5 mg/l compared to a mean Cl concentration of 100±75 mg/l for secondary treated wastewater.

In summary, average rural stream water quality for the four geoclimatic areas was relatively uniform. The water quality was generally good relative to proposed standards, but elevated TP concentrations even in the forested Piedmont area demonstrated the need for water quality goals and criteria to be responsive to measured local conditions, especially natural or background levels. Stream sample concentrations usually displayed large variations with respect to mean values indicating that rural nonpoint sources are highly variable in both space and time.

SUMMARY

Grab sample data from a two-year, statistical sampling study of forested and agricultural Piedmont, plus well- and poorly-drained Coastal Plain areas of the Chowan River Basin, were analyzed to permit a clearer understanding of the nature of rural runoff on an areawide basis. These analyses provided the following conclusions:

1. Neither in-stream (arithmetic average) nor net export (flow weighted) concentration data presented any clear relationships between water quality and macro land-use factors. This result points out the need for caution when employing model predictions to specific cases. Macro land-use factors do not account for varying agricultural cropping and management practices, annual weather conditions, stream border buffer systems, or other factors which can minimize the impact of agricultural activities on water quality.
2. The impact of channelizing Coastal Plain streams was most pronounced with respect to elevated NO_3-N concentrations in the channelized streams as compared to unchannelized streams which have natural swampy flood plains and channels which increase NO_3-N attenuation by denitrification and biological uptake.
3. Analyses for seasonal trends indicated that water yield and the associated nutrient yields were greater during the winter and spring seasons than during the summer and fall seasons reflecting rainfall and evapotranspiration

cycles. In analysis of seasonal flow weighted average concentration data, the models generally demonstrated significant relationships but had rather low r^2 values.

4. Measured concentrations did not display any consistent functional relationship to flow (water yield) levels. However, data showed that NO_3-N concentrations were elevated during flow conditions at a small (0.50 km^2 or 0.2 mi^2) site but not at larger (20 km^2 or 8 mi^2) sites in the well-drained Coastal Plain with similar land use. The NO_3-N attenuation was judged to be the result of in-stream dynamics.

5. Comparisons of geoclimatic areas demonstrated that the dominant variation was between the Piedmont and Coastal Plain with only relatively minor variations occurring within these two physiographic regions. The differences between the Piedmont and the Coastal Plain were judged to be due to naturally occurring physiographic variations in (a) basin characteristics, such as vegetation, soil type, and stream hydraulics; and (b) ocean proximity.

6. Assessment of point and nonpoint source impacts in one small basin verified classic point source concentration spikes with subsequent decline to intermediate levels for all investigated constituents except chloride and nitrate. Therefore, for the studied stream reach, nitrogen and phosphorus inputs which appear to come from treatment plant effluents are reduced to headwater background levels as long as the stream assimilatory capacity is not overwhelmed or natural inputs result in changed background water quality.

7. Point-in-time comparisons between headwater and downstream constituent concentrations showed small differences on a water quality basis.

8. Eighteen-month average rural stream water quality for the four geoclimatic areas was relatively uniform. The quality was generally good compared to proposed standards, but elevated TP concentrations even in the forested Piedmont area demonstrated the need for basing water quality assessments on measured local conditions, especially background or natural levels. Stream sample concentrations usually displayed large variations with respect to mean values indicating that rural nonpoint sources are highly variable in both space and time.

COMPARISON OF MONITORING TECHNIQUES

Grab and automated monitoring techniques were elevated at four of the statistical survey sites to supplement the cost-effective evaluations of these procedures to estimate rural nonpoint source nutrient yields and concentrations on an areawide basis. Consistent differences (bias) between mean value estimates obtained by grab and automated sampling techniques were documented although determination of causative effects was beyond the study scope. Therefore comparisons of point-in-time measurements obtained by grab and automated sampling systems are presented with the understanding that both procedures estimate actual field truth. Next, annual data from four sites which were both grab sampled and automated sampled were compared to assess possible differences in annual water quality values associated with monitoring methods. Finally, a sampling scheme which was flow stratified by the use of daily rainfall probability predictions was explored as a possible method to obtain more precise water yield estimates at a given sampling level because field data showed that subbasin water yield distributions were highly skewed.

STREAM MONITORING

Long-term grab were obtained from November 24, 1974 to March 19, 1977, and automated data from May 18, 1975 to March 19, 1977. All automated and grab sampling sites were operational from March 21, 1976 to March 19, 1977. During this period substudies were conducted to investigate particular sampling methodologies. Because these substudies often followed a sampling program which was built into the long-term schedule, the essentials of the long-term sampling plan are briefly reviewed followed by appropriate substudy information.

Long-Term Sampling Plan

The long-term sampling plan employed a sample time stratification (STS) strategy which has been presented in detail (Section 4). The time stratification was employed to ensure that measurements were obtained at a uniform rate throughout the study. Basically, the stratification was such that each of the 15 statistical survey sites was monitored 26 times per year at the rate of two visits (chosen by a restricted random sampling) per 28-day period. During each grab sample site visit, the flow rate was measured by standard USGS (Buchanan and Somers, 1969) procedures and a manually depth integrated water sample was obtained at the midpoint of the stream flow. Grab samples were collected and stored in preaged, acid-washed polyethylene bottles and were stored at 4 °C until laboratory analysis.

Automated sampling systems were established at five of the 15 statistical survey sites. Stream stage was recorded continuously by analog recorders; however, at one site a reliable stage discharge relationship and thus flow data could not be developed because of beaver activity. Automated samplers employed had the capability of collecting 28 discrete, 500-ml water samples. To retard constituent transformations during field storage, the plastic sample bottles were precharged with sufficient sulfuric acid to bring the sample pH below 2 as recommended by EPA Methods for Chemical Analysis of Water and Waste (1974). Each automated sampler intake manifold was at a fixed location in the stream such that a 250-ml subsample was taken at 75-mm (3-in.) stage increments, and two subsamples were composited to fill a sample bottle. The sampler was designed and operated on a sample-flush cycle as opposed to a flush-sample cycle. The time each subsample was obtained was recorded on the stage strip-chart by a relay activated pen so each sample bottle was assigned the mid-point time between samplings.

Grab vs. Automated Sampling

In Substudy A, data were collected to test whether manually depth integrated grab samples and fixed point automated samples produced similar water quality values for samples obtained at approximately the same time. Eighty-seven paired samples, one of each type, were obtained during routine visits to all five automated sites. Samples were obtained in the following manner: first, the grab sample was taken downstream from the automated sampler intake manifold; then the automated sampler was actuated to obtain a sample. The time interval between the paired samples was less than five minutes. All samples were stored at 4 °C until laboratory analysis. The samplers were in the stage activated mode between visits; and the intake systems were not cleaned or purged before taking the sample for these paired observations.

Grab and Automated Sampling and Storage

Another detailed study of the two sampling techniques was undertaken in which data were obtained at four automated sites once per week during a four-week period. The sampling procedure was to manually activate the automated sampler to take five successive samples (designated A1-A5 as explained below). Next, a manually depth integrated sample was taken (G1). The technician then installed a new intake system such that the intake manifold was in the stream approximately 150 mm (6 in.) upstream and 75 mm (3 in.) to the side of the usual sampling point. After waiting a sufficient time for all streambed disturbance to subside (5 to 30 minutes), the intake system was thoroughly flushed and two automated samples were taken (N1, N2). These represented duplicate samples with a new intake tube. Finally, a second grab sample was taken (G2). All automated samples were acid fixed, whether stored a week in the sampler or immediately returned to the laboratory. All grab samples were stored at 4 °C and returned to the laboratory. The new intake system consisted of an intake manifold and hose which has been "aged" by flushing with tap water for 24 hours. One "new" intake system was used for this entire study, so before leaving the site it was removed and the old intake manifold was cleaned (routine procedure) and reconnected. The sampler was inactive between these weekly visits. The sample procurement and disposition are summarized as follows:

1. A1 = Acid fixed, taken to the laboratory as the first sample;
2. A2 = Acid fixed, taken to the laboratory;
3. A3 = Acid fixed and left in the field sampler for one week;
4. A4 = Same as A3;
5. A5 = Same as A2;
6. G1 = Iced, taken to the laboratory;
7. N1 = Acid fixed, taken to the laboratory;
8. N2 = Same as N1; and
9. G2 = Same as G1.

COMPUTATIONS

Both grab and automated data sets were employed to calculate annual (1) water and nutrient yields, (2) volume average concentrations, and (3) time average concentrations. The computational methods employed with the grab data set are reviewed to illustrate the use of a statistical grab sampling data set with respect to employed data analyses. Data set manipulations to permit computations with the continuous stream hydrograph record plus stage-activated water sampling system are also discussed. Finally, the grab data set had no missing values for the year analyzed, but the automated data set did; thus computational methods employed to generate substitute values for the missing data are presented.

Grab Data

Computational methods for the grab data set are considered first. Annual water yield (WY) values were calculated using Equation 3.

$$WY = \sum_{i=1}^{13} \sum_{j=1}^{2} \left\{ (FLOW_{ij} * DAYS_{ij}) / AREA \right\} \tag{3}$$

where $FLOW_{ij}$ and $DAYS_{ij}$ are respectively the flow measurement and duration of the jth sampling unit of the i^{th} 28-day period, and AREA is the subbasin area. The variable time factor was employed because a sampling unit could be 12, 14, or 16 days. Annual constituent yields (CY) were computed as:

$$CY = \sum_{i=1}^{12} \sum_{j=1}^{2} \left\{ (C_{ij} * FLOW_{ij} * DAYS_{ij}) / AREA \right\} \tag{4}$$

where C_{ij} is the grab sample constituent concentration for the j^{th} sample of the i^{th} period. Annual volume average (flow weighted) concentrations (VAC) were computed by dividing the annual constituent yields by the annual water yield. Annual time average concentrations (TAC) were computed for each site as:

$$TAC = \sum_{i=1}^{13} \sum_{j=1}^{2} (C_{ij} * DAYS_{ij} / DAYS) \tag{5}$$

where DAYS represents a time interval of 364 days. Equations 3-5 reduce to a more common format if the sampling unit duration is chosen to be constant.

Automated Data

Hourly water yield values were calculated by digitizing the hydrographs on an hourly basis and employing the appropriate stage-discharge relationship. Hourly constituent transports were also determined for the automated data set. The stage activated samples did not obtain samples on an hourly basis so a method of assigning hourly values had to be chosen.

The hydrographs had considerably steeper sections during the rising portion of runoff events (more than two water samples/hr) than during the recession limb (less than one sample/hr) and these events were usually separated by relatively long baseflow periods (less than one sample/day). Thus, water sampling frequency varied across the hydrograph with samples being taken as often as several per hour on rising limbs of runoff events to as infrequently as less than one per week during nonrunoff conditions. So that the first sample on the rising limb of an event would not impact the possible long antecedent baseflow assessment, the assignment method judged to best represent the physical system for calculating constituent yield elements ($CY_{k,i}$) was:

$$CY_{k,i} = C_k Y_{k,i} \tag{6}$$

where C_k is the concentration of the k^{th} water sample and $Y_{k,i}$ is the i^{th} 5-minute water yield during the time interval between the k and k+1 water samples. C_i was a special case in which the concentrations were extended backward to time zero because no sample was obtained when the instruments were initially activated. Five-minute water yields for these calculations were obtained by linear interpolation between hourly values. The 5-minute constituent yield values were summed on an hourly basis and the resulting values were used in data analyses.

The automated sampling data records for each site are summarized in Table 27 which shows that the P8 system was 100 percent operational and the other three systems were operational more than 95 percent of the year. Analytical techniques were employed to generate substitute values for the inoperable hours. The hourly water yields were highly correlated for sites within either the Piedmont or Coastal Plain so linear regressions were employed on adjacent site values to generate missing water yield values. No satisfactory regression method could be formed to predict concentrations at a site so the year was broken into four, 3-month seasons (November-December corresponding to winter); and seasonal flow weighted average concentrations were employed to generate missing hourly constituent yield values.

The measured and synthesized automated data were combined to provide a complete hourly data record. Annual yields and volume average concentrations were computed with respect to definitions. On an hourly basis, constituent yields were divided by water yield to obtain volume average concentrations. These hourly volume average concentrations were arithmetically averaged to provide annual psuedo-time average concentrations which are simply referred to as automated time average concentrations.

RESULTS AND DISCUSSION

Grab vs. Automated Sampling - Substudy A

Constituent mean values from the initial comparison of grab and automated sampling at five sites and the significance of differences determined by an analysis of variance are presented in Table 28. The analysis of variance was performed on logarithmically transformed paired sample data because measurement errors were considered to be proportional to the magnitude of the measured

TABLE 27. AUTOMATED DATA RECORD SUMMARY (MARCH 21, 1976-MARCH 19, 1977)

Site	Percent record complete	Hours missing	Dates missing
F03	97.8	192	January 28-February 5
A01	97.7	195	July 17-July 25
P08	100.0	0	None
P10	98.6	119	January 10-January 15

TABLE 28. COMPARISON OF GRAB AND AUTOMATED SAMPLES AT FIVE SITES

Parameter	Grab mean concentration mg/l	Automated mean concentration mg/l	Statistical significance of difference	Total number of values
COD	25.10	39.40	$0.01<P<0.05$*	126
TOC	8.10	13.20	$P<0.01$**	120
TP	0.13	0.18	$P<0.01$**	174
TKN	1.22	1.49	$0.01<P<0.05$*	174
NO_3-N	0.09	0.08	$P>0.10$	168
Cl	6.19	6.71	$0.01<P<0.05$*	168

*Significant
**Highly Significant

value. The error term for testing differences according to collection method (1 degree of freedom) was the method and site interaction (4 degrees of freedom). The results of this experiment indicated that differences ($P<0.10$) between COD, TOC, TP, TKN, and Cl concentrations measured by grab and automated samples existed while there was no evidence of a difference ($P>0.10$) for NO_3-N concentrations. The grab mean concentrations were less than the automated mean concentrations by 36, 39, 28, 19, and 8 percent for COD, TOC, TP, TKN, and Cl respectively.

Grab vs. Automated Sampling and Storage

This detailed experiment was performed to assess possible sources of observed differences between parameter concentrations measured by manual, depth-integrated, grab sampling and fixed-point, automated sampling. Several possible contributing factors were evaluated statistically by an analysis of variance which employed logarithmically transformed data. Mean values and significance of differences are summarized in Table 29. Four single degree of freedom comparisons were examined. Although these are not all orthogonal, they comprise the comparisons of interest. The error term was a composite of first order interactions of visits and sites for the nine samples taken. For the constituents considered, the experiment showed ($P<0.10$) that when a sample-flush cycle was employed, the first automated sample (A1) concentrations of COD, TOC, TP, and TKN from samplers which were inactive for a week were 55, 60, 71, and 34 percent greater than the concentration of samples (A2, A5) taken immediately thereafter; i.e., a first sample effect existed. For comparisons in which the first sample was excluded, it was found that:

TABLE 29. EXPERIMENTAL STUDY OF AUTOMATED SAMPLER AT FOUR SITES

Effect tested	Parameter	Argument mean concentration mg/1	Standard mean concentration mg/1	Statistical significance of difference
First sample; A1 vs. A2, A5	COD	82.600	53.300	$P<0.01$**
	TOC	30.400	19.000	$P<0.01$**
	TP	0.040	0.140	$P<0.01$**
	TKN	1.590	1.190	$0.01<P<0.05$*
	NO_3-N	0.630	0.079	$P>0.10$
	Cl	5.990	6.020	$P>0.10$
Intake systems; N1, N2 vs. A2, A5	COD	51.100	53.300	$P>0.10$
	TOC	16.300	19.000	$P>0.10$
	TP	0.220	0.140	$P>0.10$
	TKN	1.020	1.190	$0.05<P<0.10$
	NO_3-N	0.098	0.079	$P>0.10$
	Cl	6.310	6.020	$P>0.10$
Storage; A3, A4 vs. A2, A5	COD	42.400	53.300	$P<0.01$**
	TOC	16.100	19.000	$0.05<P<0.10$
	TP	0.120	0.140	$P>0.10$
	TKN	1.090	1.190	$P>0.10$
	NO_3-N	0.089	0.079	$P>0.10$
	Cl	6.250	6.020	$P>0.10$
Grab vs. routine automated G1, G2 vs. A2, A5	COD	42.300	53.300	$0.01<P<0.05$*
	TOC	12.500	19.000	$P<0.01$**
	TP	0.140	0.140	$P>0.10$
	TKN	0.960	1.190	$0.01<P<0.05$*
	NO_3-N	0.083	0.079	$0.01<P<0.05$*
	Cl	4.780	6.020	$P<0.01$**

*Significant
**Highly Significant

1. concentrations from intake systems which had been employed for routine field sampling for extended periods compared to a "new" intake system were the same, except for TKN, in which case the old intake system mean value was 14 percent less than the new intake system value;

2. acid-fixed automated samples (A3, A4) stored in the field for one week had COD and TOC concentrations approximately 20 percent lower than acid-fixed automated samples (A2, A5) returned directly to the laboratory; and

3. manually depth integrated grab samples (G1, G2) which were iced and returned to the laboratory for analysis had 21, 34, 19, and 21 percent lower COD, TOC, TKN, and Cl concentrations, respectively but 5 percent higher NO_3-N concentrations than automated samples (A2, A5) obtained with the routine intake system, acid fixed, and returned to the laboratory.

Annual Concentration and Yield Comparisons

The annual volume average concentrations obtained by simple time stratification (STS) grab sampling and stage-activated automated sampling at four sites are presented in Table 30. For a given site, relatively large differences can be observed between the grab and automated estimates. Because the grab to automated concentration ratio varied among constituents at a site, no consistent factor related the two estimates. Further, for each water quality constituent the grab to automated concentration ratio varied among the sites; thus a factor relating the two estimates which was independent of site did not exist. The significance of difference between the grab and automated vol-

TABLE 30. COMPARISON OF GRAB AND AUTOMATED FLOW WEIGHTED CONCENTRATIONS AT FOUR SITES, (MARCH 1976-MARCH 1977)

Parameter	Subbasin	GVAC* mg/l	AVAC** mg/l	GVAC/AVAC %
COD	F3	23.7	42.0	56
	A1	12.9	41.1	31
	P8	54.5	56.4	96
	P10	38.4	81.9	47
TOC	F3	5.86	12.6	47
	A1	4.80	13.1	37
	P8	9.76	14.3	68
	P10	9.04	21.4	42
TP	F3	0.094	0.139	68
	A1	0.085	0.190	45
	P8	0.176	0.256	69
	P10	0.174	0.521	33
TKN	F3	1.16	1.32	88
	A1	0.96	1.45	66
	P8	1.95	1.87	104
	P10	2.40	2.46	97
NO_3-N	F3	0.033	0.054	61
	A1	0.112	0.092	122
	P8	0.075	0.074	101
	P10	0.372	0.413	90
Cl	F3	3.50	4.58	76
	A1	3.28	4.00	82
	P8	4.51	6.44	70
	P10	10.25	9.02	113

*GVAC - Grab Sampling Flow Weighted Concentration
**AVAC - Automated Sampling Flow Weighted Concentration

ume average concentration estimates was evaluated employing a two-sided t-test utilizing logarithmic transformed paired samples (values for the two methods at each of four sites). The test indicated ($P<0.10$) that annual, volume average, grab concentration estimates of COD, TOC, and TP were less than automated sampling values by a statistically significant amount averaging about 50 percent; for TKN, NO_3-N and Cl grab sampling was less by an average of about 13 percent, not significant statistically.

The ratio of the annual, time average concentration to the annual, volume average concentration obtained by both grab and automated sampling is presented in Table 31. For some nonpoint sources such as sediment, higher concentrations occur during high flows in which case the time average concentration (TAC) is less than the volume average concentration (VAC). However, the values in Table 31 indicate that this is not always the case for the measured constituents and

TABLE 31. RATIOS OF TIME AVERAGE TO FLOW WEIGHTED CONCENTRATIONS AT FOUR SITES, (MARCH 1976-MARCH 1977)

Parameter	Subbasin	Grab ratio	Automated ratio
COD	F3	1.12	1.07
	A1	0.91	1.18
	P8	0.74	1.16
	P10	0.59	1.02
TOC	F3	1.14	1.13
	A1	0.90	1.17
	P8	1.43	1.51
	P10	0.74	1.04
TP	F3	0.96	0.95
	A1	0.98	0.77
	P8	0.93	1.25
	P10	0.87	0.96
TKN	F3	1.00	0.91
	A1	0.91	0.94
	P8	0.74	1.12
	P10	0.49	1.01
NO_3-N	F3	1.71	1.00
	A1	0.75	0.48
	P8	0.63	0.62
	P10	0.50	0.78
Cl	F3	0.91	0.96
	A1	1.05	0.90
	P8	1.59	1.25
	P10	0.94	1.18

computational methods employed. The fact that many values are approximately 1.0 implies that concentrations are not correlated with flow. Use of a two-sided t-test on log-transformed paired summary values found evidence of a statistically significant difference in only 2 of the 12 data sets; for grab sampling the time averaged mean for TP was less than the volume average, while for automated data the time average values exceeded the volume average (in both cases $0.05<P<0.10$).

The annual grab and automated water yield estimates obtained at four automated sampling sites are presented in Table 32. Relatively large differences between paired samples can be observed. However, a two-sided t-test employing logarithmic transformed data for paired samples provides no evidence of a statistically significant difference between estimates by the two methods ($P<0.10$).

TABLE 32. COMPARISON OF GRAB AND AUTOMATED WATER YIELD VALUES AT FOUR SITES, (MARCH 1976-MARCH 1977)

Subbasin	Grab water yield		Automated water yield		Grab yield/ auto yield
	mm/yr	(in./yr)	mm/yr	(in./yr)	%
F3	208	(8.2)	256	(10.1)	81
A1	216	(8.5)	366	(14.4)	59
P8	227	(8.9)	119	(4.7)	191
P10	297	(11.7)	248	(9.8)	120

Rainfall Probability Sampling

Historical precipitation data reported by Saucier, et al. (1973) indicated the mean annual rainfall for the study area of the Chowan River Basin is 1.1-1.3 m/yr (43-50 in./yr) and a 40-yr record (1931-70) also indicated that the mean monthly rainfall was relatively uniform having an average of 100 mm (4.0 in.) with the maximum of 170 mm (6.7 in.) occurring in July and the minimum of 70 mm (2.8 in.) occurring in October. Correspondingly, Busby (1966) reported that annual water yield for the study area is 250-380 mm/yr (10-15 in./yr).

The annual average rainfall was 1 m/yr (39 in./yr) at a study site during the study period according to National Oceanic and Atmospheric Administration (NOAA) data presented in the Hydrologic Information Storage and Retrieval System (Wiser, 1975). The annual water yield estimates obtained by simple time stratified (STS) sampling at each of the 15 statistical survey sampling sites (38 measurements per site) are summarized in Table 33. The range of the annual water yield estimates was approximately 0.1-1.0 m/yr (4-40 in./yr). Thus while the STS sampling approach probably provided unbiased estimates of the overall mean annual water yield (0.34 m/yr or 13.3 in./yr), the one sample per two-week frequency did not provide a very precise estimate of the annual water yield for the 15 statistical survey streams during the sampling period.

Further analysis of the water yield measurements for each site indicated that the distributions were highly skewed (Table 33); i.e., many low flow measurements and only a few high flow measurements were made at each site. Stratified sampling on the basis of the measured parameter may provide a more precise estimate of the mean at a given sampling intensity compared to simple random sampling for skewed distributions (Cochran, 1977). In practice, this suggests a method of stratifying stream measurements based upon flow regime.

Daily rainfall probability predictions provide a mechanism for stratifying days into two strata with either a high or low chance of rainfall and hence runoff. As a first approximation, daily water yield should be proportional to daily rainfall. Naturally other factors, such as soil moisture and rainfall intensity, impact this relationship; but as an initial attempt, it seem appropriate to examine the probability of rainfall as an indication of flow regime. To pursue this approach, five years of NOAA rainfall predictions (U.S. Department of Commerce, 1971-76) and rainfall measurements (Wiser, 1975) for a precipitation recording station in the general vicinity of our study (Edenton, North Carolina) were compiled. The contingency table for these data, Table 34, indicating relationships between rainfall predictions and measured rainfall

TABLE 33. GRAB SAMPLING WATER YIELD AND SKEWNESS VALUES, (JULY 1975-NOVEMBER 1976)

Subbasin	Water yield mm/yr	Water yield (in./yr)	Skewness value nondimensional
F-1	376	(14.8)	5.6
F-2	345	(13.6)	3.4
F-3	348	(13.7)	3.5
F-7	211	(8.3)	2.9
A-1	417	(16.4)	4.3
A-4	330	(13.0)	5.7
A-8	437	(17.2)	4.6
W-3	942	(37.1)	4.6
W-4	940	(37.0)	1.5
W-8	127	(5.0)	1.9
W-10	175	(6.9)	1.9
P-8	124	(4.9)	4.1
P-10	132	(5.2)	5.1
P-11	76	(3.0)	4.3
P-13	102	(4.0)	3.0
Mean	338	(13.3)	

TABLE 34. DAILY PRECIPITATION PROBABILITY VERSUS DAILY PRECIPITATION AT EDENTON, N.C., OCTOBER 1971-OCTOBER 1976

Forecast probability of precipitation, in percent	Daily precipitation range, in mm (in.); occurrence, in percent					
	0.0-T* (0.0-T)	0.1-12.4 (0.01-0.49)	12.5-25.2 (0.50-0.99)	25.3-37.8 (1.00-1.49)	≥37.9 (≥1.50)	Sum of Ranges
0	25.00	1.99	0.17	0.11	0.06	27.89
10	14.30	2.37	0.11	0.06	0.00	16.84
20	11.00	3.64	0.72	0.33	0.28	16.23
30	7.62	2.82	0.77	0.22	0.17	11.60
40	4.36	2.65	0.55	0.39	0.22	8.17
50	2.10	2.10	0.61	0.17	0.06	5.02
60	2.04	2.71	0.88	0.22	0.11	5.96
70	0.94	2.10	0.44	0.17	0.28	3.92
80	0.55	1.27	0.77	0.28	0.11	2.98
90	0.22	0.22	0.23	0.06	0.06	0.83
100	0.00	0.11	0.22	0.06	0.17	0.55
Sum of Probabilities	68.97	21.98	5.52	2.04	1.49	100.00

*T = Trace

shows that either no rainfall or less than 13 mm (0.5 in.) of rainfall was measured approximately 90 percent of the time and that as the daily rainfall increased, the likelihood of occurrence decreased rapidly.

This daily rainfall distribution indicates a cause of the skewed daily water yield estimates provided by STS grab sampling. However, for a specified sampling level, utilization of rainfall predictions can provide an increased proportion of high flow measurements as compared to simple random sampling. If a field trip were made every time the precipitation probability reached or exceeded some chosen level, the chance of measuring streamflow during a significant rainfall would increase as the rainfall probability increased. This is illustrated in Figure 15 where the predicted number of trips per year and the expected number of "successes" for several minimum rainfall probability levels of field trip initiation are shown. Success was defined as a daily rainfall of 13 mm (0.5 in.) or greater which was the amount assumed to result in elevated streamflows. As a further refinement the rainfall distribution of the successes is shown in Figure 15. As an example, if a sampling trip were made only when the probability of rainfall was 80 percent or greater, about 7 of 16 field trips per year would result in elevated stream flow measurements; and the rainfall intensity would be greater than 39 mm (1.5 in.) about once per year.

Thus, the chance of predicting significant rainfall and correspondingly the chance of measuring elevated stream flow can be increased by employing rainfall probability predictions as compared to simple random sampling. Because the distributions of daily water yield for small subbasins in the study area of the Chowan Basin were skewed, a sampling plan stratified by the probability of rainfall instead of a simple time stratification may have allowed increased precision of annual water yield estimates for a given sampling intensity. Basically this method permits a monitoring agency to put a small fraction of resources into measuring baseflow conditions and a larger fraction into the more difficult measurement of high flows. As a consequence, better estimates of runoff conditions and annual yields may be obtained on an areawide basis while still utilizing the statistical approach.

SUMMARY AND CONCLUSIONS

Statistical sampling methods can be employed to measure the mean areawide contribution of chemical species from rural nonpoint sources as an alternative to the more difficult and often impractical complete monitoring approach. Grab sampling and automated sampling are two common methods of assessing stream water quality which can be employed in a statistically designed sampling program. Water quality based results of the grab and automated sampling comparisons provide information which can be utilized to design sampling plans that minimize the variance attributable to sampling methodology.

Point-in-time comparisons of manually depth integrated and fixed point automated samples were conducted for COD, TOC, TP, TKN, NO_3-N, and Cl. One substudy showed that manually depth integrated samples provides lower estimates of COD, TOC, TP, TKN, and Cl concentrations (36, 39, 28, 18 and 8 percent, respectively) than the first sample obtained from fixed point automated samplers in routine stage-activated operation when both samples were preserved by refrigeration until laboratory analysis. Data from a study to determine the relative contribution of sample procurement, preservation, and storage on automated sample parameter concentrations indicated that the sample-flush sampling cycle produced a "first" sample effect; that is, the first sample obtained from an automated sampler operating in the sample-flush mode which was inactive for approximately a week had about 60 percent higher concentrations of COD, TOC, TP, and TKN than samples taken immediately thereafter. About 20 percent lower concentrations of COD and TOC were observed for manually depth integrated samples preserved by cooling compared to fixed point automated sample preserved by acid fixation. Finally, acid-fixed automated samples which were stored in the field for a week had about 20 percent lower COD and TOC concentrations than

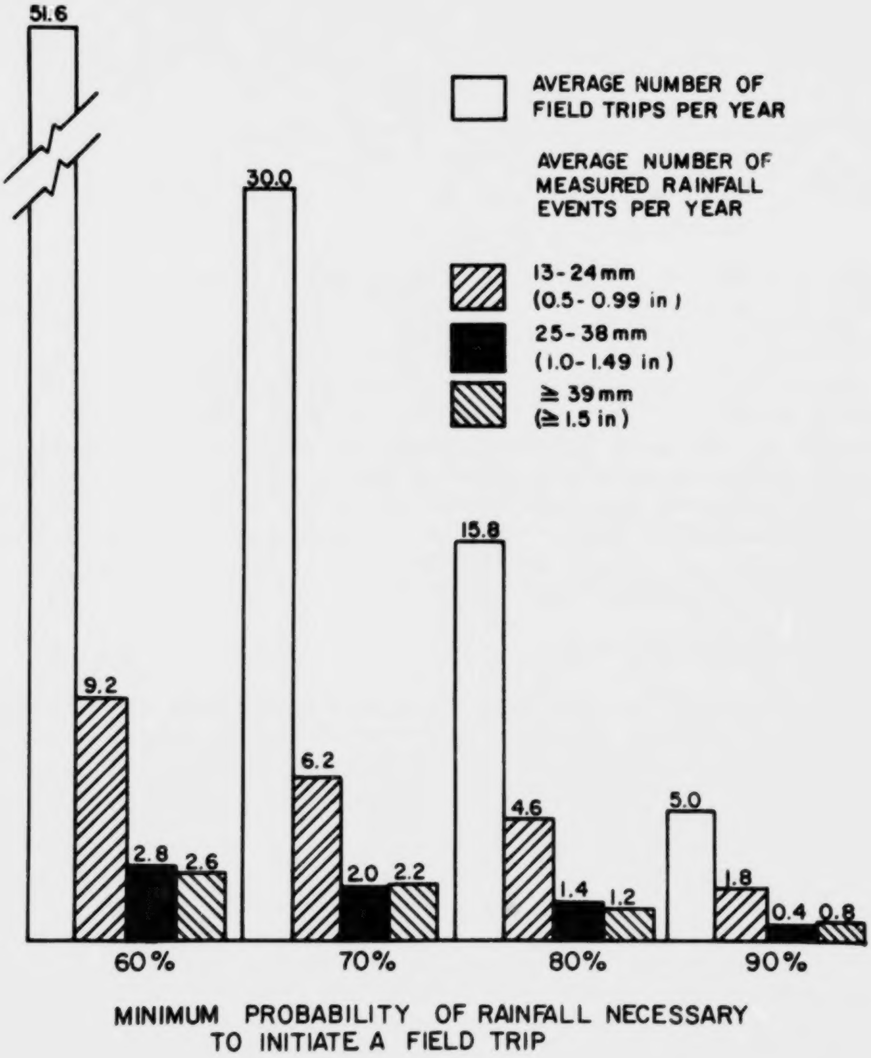

Figure 15. Example of rainfall forecasts to predict sampling events.

acid-fixed automated samples returned immediately to the laboratory for analysis. These data indicate that COD and TOC were the parameters impacted most when recommended procedures were employed in routine data acquisition. Furthermore, the sample-flush cycle caused a first sample effect that had a significant impact on several parameter concentrations.

Annual volume average concentration and water yield estimates were obtained at four sites by routine operation of both stage-activated automated samplers with stage recorders and simple time stratified grab sampling. Results indicated that about 50 percent lower COD, TOC, and TP estimates were obtained by the grab sampling method. Although rather large differences were observed for the water yield estimates, the data did not indicate any statistically significant difference between the two methods. Due to confounding factors associated with the two sampling methodologies, it was not possible to specifically define the source of the concentration differences. However, investigators should be alerted to the limitations of estimates using one or the other of these sampling methods.

Comparison of annual water yield estimates from the 15 statistical survey sites to historic values for the study region verified that simple time stratified (STS) grab sampling provided reasonable estimate of areawide annual water yield; however, the precision of the individual estimates was low. Sampling theory indicates that increased estimate precision of skewed populations, such as recorded by the STS sampling of water yield, can often be achieved by stratification on the population variable. Thus, the potential of employing daily weather predictions as a means of time stratification to improve water yield estimate precision at a given sampling intensity was demonstrated.

In conclusion, the effect of sampling methodologies on water quality measurements in no way lessens the need to establish adequate data bases in order to provide a foundation for sound scientific assessment of rural nonpoint sources. The information presented should aid future investigators and monitoring agencies in better understanding stream monitoring data and designing improved data acquisition systems.

SECTION 6

ALGAL POPULATIONS IN TWO SMALL STREAMS

by

Augustus M. Witherspoon and Thomas R. Fisher*

INTRODUCTION

In recent years much attention has been focused on the pollutional burden carried in streams of the United States. The concern has been generated in part from the objectional aesthetic deterioration of waters receiving the discharge of all streams, large and small. Algal blooms of increasing frequency, duration, and magnitude have played a large part in generating social pressure to rectify man-induced environmental deterioration. The resulting legislation has been directed at monitoring water quality and detecting and correcting deleterious changes.

Knowledge is incomplete on the contributions made to this problem of algal growth by elements of rural runoff as it occurs in small headwater streams of a drainage basin. The contribution of nutrients made by point sources, and the characteristics of algal populations in impoundments and in slow-moving large streams are better understood.

The objectives of this phase of the overall study were to appraise the algal populations found in small drainages, to list the species found, to measure the population biomass and to apply probability sampling to the study of population changes. A further objective was to appraise the usefulness of a static algal assay technique developed and recommended at the national level by the Environmental Protection Agency (Anon. 1971).

CONCLUSIONS

In these two small streams, the algal community included many species with only a few dominant forms.

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* Manuscript assembled and edited by Don W. Hayne.

Algal biomass was usually low, but reached high levels occasionally. Explanation for fluctuations in biomass must be sought in processes bringing algae into the flowing water from the bottom or from nearby water or land, rather than in growth of the ambient plankton itself.

Algal population levels in these headwater streams are limited by fluctuations in these unknown input processes, by high flushing rates, and possibly by poor light, not by nutrients; ambient populations are only a fraction of the potential levels realized in laboratory assay and possibly in lower parts of the same stream.

Algal assays indicated potential growth limitation most frequently by nitrogen, next by factors other than nitrogen or phosphorus, rarely by phosphorus alone. Such potential limitations apply in reality only at some hypothetical downstream location and condition, not to populations present in these small streams.

Within-stream fluctuations in potential nutrient limitation suggest a within-stream heterogeneity in nutrient balance.

RECOMMENDATIONS

The origin of planktonic algae in small headwater streams should be further studied to determine the relative contribution from the periphyton, from bodies of standing water, and from the soil surface.

Further investigation should be made of the possible synchrony between plankton pulses in small drainage basins, in principal tributaries and in the main river, to determine what role the populations in headwater streams may play in blooms in the estuary.

The bottle assay method should be refined and used to determine by how far the nutrient concentrations in small drainages fall short of those required to support an algal bloom.

SITES OF STUDY AND METHODS OF PROCEDURE

These algal studies were carried out in two streams, arbitrarily chosen for more intensive study from the set of 15 small drainage basins chosen at random for the overall study. One of these streams lay in the poorly drained Coastal Plain while the other was in the forested Piedmont. Several sampling stations or subsites were established on each stream.

The piedmont stream (Quarrel Creek in Brunswick County, Virginia, designated F-3) lay in a rolling piedmont location entirely wooded along the stream and for some distance away from it in both directions with a mesic hardwood forest. Subsites from which data were used were numbered 20, 22, 23, 24, 25 and 28 with 20, 22, 24, 25 and 28 in one direct line of flow and 23 on a tributary just above the confluence which lay just above 24. A few other subsites were sampled at irregular intervals. The stream had many looping hairpin turns, especially in the broader part of the forested flood plain which had a thick deposit of leaves mixed with sand from previous flooding. The banks were clay 0.5-1.5 m high and the stream bottom was sand with some forest debris. This stream was 2-5 m wide, 0.2-0.4 m deep, and recorded velocities were 0.16-0.31 m per sec, all measurements increasing downstream. The length of stream above the lowest subsite used here (25) was 10.2 km. These characteristics suggest that this stream volume was replaced in 9-18 hours.

Within the stream there were many rocks covered with algae and an unidentified macrophyte up to 0.6 m long, carrying algal periphyton. Blue-green algae were observed growing on sand in places where the turbulence was not great. There were also many standing pools with large algal populations (mostly filamentous greens and blue-greens); some of these had a direct connection with the stream and slowly drained into it. Thus the F-3 system was a winding natural stream with many internal sources of algae as well as some external but the flushing rate was such that there could not be much growth of planktonic algae within the stream itself.

The coastal plain stream (Flat Swamp in Hertford County, North Carolina, designated P-10) had been channelized and was virtually without pools or bends, 1-3 m wide and 0.2-0.5 m deep. Subsites from which data were used were numbered 1, 2, 3, 4 and 6 with 1, 3, 4 and 6 in one direct line of flow and 2 on a tributary just above the confluence which lay just above 4. Several other subsites were sampled at irregular intervals. The banks of P-10 were clay sub-soil with a U-shaped cross section typical of channelized streams. The bottom was of clay chunks and some sandy clay with virtually no rock or hard substrate. The water flowed straight and fast; litter did not accumulate to any extent. Estimates of water velocity ranged from 0.41-0.70 m per sec; with a total length of 6 km above the lowest downstream subsite (6) water was replaced in the stream every 2-4 hours. The water was stained with dissolved organics and in addition carried a load of fine clays and other suspensoids with the bottom not visible if the water was deeper than 0.3 m. Although agricultural fields dominated the drainage basin, a margin of mostly deciduous trees bordered the entire length of the stream and provided heavy shade when leafed out. Thus light was not plentiful during most of the year.

Possible sources of algae in the P-10 watershed were numerous. During one visit in winter the cultivated fields had a noticeable green cast, indicating a surface bloom of soil algae; clumps of filamentous algae were observed growing on wet soil of empty fields. Other sources of algae were nearby pocosin swamps; one of these appeared to be fed directly by the effluent from a pig farm and to be covered by a green layer of algae. Thus, algal concentrations in the stream probably reflected local extrinsic events and not intrinsic conditions.

The basic schedule for making algal collections at these two subbasins was the same as that for the overall study, that is, two visits at randomly selected times within each four-week period. Algal collections were made on this schedule from the first visit (24 November 1974) through the seventh (7 March 1975) and then the schedule was shifted to half this frequency because of the cost of processing the samples, and this schedule was used through visit 34 (9 March 1976). After examining the data from the algal assays, however, it was necessary to discard results during the period of developing the technique prior to visit 16 (9 July 1975). Thus, information is available on the identity of the algal species and on their numbers and biomass from November 1974 to March 1976, but for the algal assays the only information is for the shorter period of July 1975 to March of the following year.

Typically, at each field visit to a sampling point water samples were taken for algal study and for chemical analysis and a flow measurement was made. Water samples were collected with a bottle, manually integrating over the water column in each stream. Samples for algal assay were iced; those for enumeration of endemic algae were preserved with Lugol's solution in the field. Samples were brought to the laboratory according to the work schedule, sometimes within the same day but never after more than three days.

The endemic algae were counted and identified within one week after arrival of the sample in the laboratory. From each water sample, a 100 ml subsample was counted in an Utermohl settling chamber using an inverted microscope. Fields were counted until 100 individuals of each of the more common species had been recorded. From each sample the volume of 10 individuals of each species was estimated using an appropriate solid geometric model depending upon the shape of the organism. The number of cells per ml was calculated for each species, using a constant unique to each sample (depending upon the number of fields counted, the field area and the settling chamber area). The total cell volume for each species was then estimated from the average cell volume and the estimated number of cells per ml. Cell volume was taken to equal biomass assuming that density was unity (Vollenweider 1974).

To compare the endemic algal population levels observed in the streams with the potential levels as measured in the algal assays, the latter values had to be converted to rough approximations in similar units. For this reason the optical density measurements of maximum standing crop for the unenriched controls were converted to cell numbers using data from Forsythe (1973, Table 7).

Diversity and evenness were calculated here, based upon the genus taxon. Weber (1973) suggested in reference to macroinvertebrates, that diversity, and especially "equitability" of Lloyd and Ghelardi (1964) might be sensitive indices to water quality. In following this suggestion with algae, we have used the Shannon-Weaver form (Poole 1974, Pielou 1975):

$$H' = c\sum_{i=1}^{s} p_i \ln p_i$$

where s = number of genera

p_i = proportion of the total number of individuals in the ith genus

c = constant to state results as logarithms to base 2.

The Margalef evenness value has been calculated as the diversity value divided by the value for maximum diversity possible with the observed number of genera.

The importance of the algae in transporting carbon, nitrogen and phosphorus was estimated for each collection. First the carbon, nitrogen, and phosphorus contents of the algal cells were estimated from the biomass, assuming that cell organic carbon represents 10 percent of algal fresh weight (Vollenweider 1974), and that the atomic C:N:P ratio is 100:16:1 (Redfield et al. 1963, Winberg 1971). These assumptions result in an uncertainty of 3-5 in the final results (Vollenweider 1974), i.e., the correct value lies in the interval 1/3-1/5 to 3-5 times the calculated values. These values were then calculated as percentages of total organic carbon, total nitrogen (nitrate plus Kjeldahl) and total phosphate as determined by chemical analysis of the particular water sample.

The measurements of algal biomass made in these streams were converted to approximate equivalent values of chlorophyll a through use of the data of Nichols (1976).

The Environmental Protection Agency has developed an algal assay procedure which has been recommended as useful in studies of water quality (Weiss and Helms 1971, Fitzgerald 1972, Forsythe 1973, Maloney et al. 1972). This procedure is a static culturing system which tests the effect of additions of nutrient on the growth rate and maximum standing crop of a standard test alga. The results of the static bioassays have been used to determine limiting nutrients, and can be used to assess the growth potential for algae of a particular body of water. Our algal assays used this Provisional Algal Assay Procedure Bottle Test (Anon. 1971).

Upon receipt, water samples for algal assay were micropore (0.45 micron) filtered to remove living cells and then used to prepare a series of 250 ml Erlenmeyer flasks with 100 ml water each. Three replicated flasks (sometimes two) each for 10 treatment levels received differing spikes of nitrogen and phosphorus according to the experimental design detailed below. Sodium nitrate was added for nitrogen at 0.75, 0.225 and 0.75 mg/l, and potassium phosphate for phosphorus at 0.005, 0.015, and 0.050 mg/l. Each flask was then seeded with 1,000 cells/ml of Selenastrum capricornutum maintained and prepared for inoculation as directed in the reference. The seeded flasks were held in a constant temperature room ($24^{\circ} \pm 1^{\circ}$ C) under a continuous light regime of 400 ft-c. With each set of flasks (which usually comprised all assays for a single visit to a stream), three replicate flasks were also seeded with the same cell concentration of the test organism on the standard culture nutrient medium and held for the same period under similar temperature and illumination conditions. These "medium controls" served an important function; their erratic behavior before visit 16 demonstrated that the laboratory procedure was not under control.

The optical density of the algal standing crop was measured daily using a Beckman spectrophotometer at 750 nm until increase was less than 5 percent in a day. For each flask two parameters were calculated from the set of successive daily measurements. Optical density readings were used in these calculations rather than estimated cell density, following the finding of Weiss and Helms (1971) that optical density is highly correlated with algal biomass. Maximum standing crop was taken to be the first point reached after which the daily increase in biomass was less than 5 percent. Maximum specific growth rate was the maximum value of the specific growth rate (or instantaneous rate of growth) which was calculated for each day by the usual relationship as follows:

$$\text{specific growth rate} = \frac{\ln(X_2/X_1)}{t}$$

where X_2 = biomass at the end of the time interval

X_1 = biomass at the beginning of the time interval

t = elapsed time in days, here 1 day.

Units of this quantity are day^{-1}.

An argument can be made that maximum specific growth rate may be a less useful response variable here than maximum standing crop, because growth rate may be limited by rate of uptake of available nutrients. Recent research on the uptake kinetics of nitrate, ammonia, and phosphate (Eppley et al. 1969, Fuhs et al. 1972, MacIsaac and Dugdale 1969, Stanley and Hobbie 1977, Balducci 1977) have documented a generally hyperbolic relationship between the rate of uptake of a nutrient and its concentration. Uptake is usually expressed as a velocity (uptake/standing crop, both in units of N or P) which is equivalent to a specific growth rate in terms of either nitrogen or phosphorus. The two parameters used to define the curve are Vmax, the maximum or saturated uptake velocity (the asymtote), and K_t, the substrate concentration at one-half the maximum uptake velocity. At concentrations exceeding K_t, at most a doubling in uptake velocity can occur, and at concentrations exceeding two or three times K_t difficulty may be anticipated in detecting increased uptake velocity with increased nutrient concentration. Although K_t varies depending on environment

(MacIsaac and Dugdale 1969), most estimates fall into the ranges 0.01-0.05 mg N/l and 0.001-0.005 mg P/l (Eppley et al. 1969, MacIsaac and Dugdale 1969, Fuhs et al. 1972). Stanley and Hobbie (1977) and Balducci (1977), working in the lower Chowan River, estimate K_t as 0.01-0.02 mg N/l and 0.004-0.005 mg P/l, respectively. Considering the average concentrations in the two streams it seems that little relationship between concentrations and growth rate should be expected, especially for stream system P-10. The concentrations in F-3 were closer to K_t values than are those in P-10. Except in lakes or reservoirs where concentrations are equivalent to or less than K_t values (e.g., Maloney et al. 1972), maximum specific growth rate may not be as useful as maximum standing crop in algal assays.

An incomplete factorial design was used for the algal assay procedure, following somewhat the suggestions of the publication describing the method (Anon. 1971). A factorial design had the advantage that certain "contrasts" could be examined efficiently and without ambiguity by planning certain combinations of spikes, but in this context the design had the practical difficulty that inclusion of all treatments and combinations of treatments at all levels would have been costly in terms of separate treatments. In the incomplete design used here, certain combinations of treatments were dropped to reduce labor costs, retaining only the marginal treatments of nitrogen and phosphorus used alone along with the diagonal set of combinations, as shown below. As a result, with four levels each of nitrogen and phosphorus (counting in each case the 0 level of each for unfortified natural water) the cost of each assay, per replication, was reduced from 16 to 10 bottles (plus medium control). The design used was as follows:

NOP3	-	-	N3P3
NOP2	-	N2P2	-
NOP1	N1P1	-	-
NOPO	N1PO	N2PO	N3PO

Here, NOPO represents the zero level of addition for both nitrogen and phosphorus, NOP1 the zero level for nitrogen and the first level for phosphorus, etc.

The 10 combinations of treatments listed above, along with the replicated trial of the growth medium alone allowed a testing of treatments with ten degrees of freedom. A very large number of possible contrasts could have been examined here, even though some of the traditional factorial contrasts had been confounded in the incomplete design. It was not possible to find a set of orthogonal contrasts that included all the comparisons of possible interest and that did not include contrasts of no interest. Therefore, seven contrasts (not all mutually orthogonal) were set up to examine what seemed to be the important biological questions. For each contrast the same error term was used, based upon the variability among replicated flasks treated alike.

In the present context the term "contrast" refers to a comparison between algal responses to treatments. When a contrast has a positive numerical value it means that the first element (response) of the comparison exceeded the second; a negative contrast indicates that the first element was less than the second.

The contrasts used in the analysis concentrated on detecting the average change from addition of the three levels of nitrogen, for example, rather than testing for a linear response to the series of levels. This choice was made for two reasons. First, testing for a linear response would require that the ambient level of nutrient be determined, in each case to be added to the spike values, with confusion from the fact that at least a small part of the measured ambient level had been removed with the live cells. Second, if factors other than nitrogen or phosphorus were potentially limiting, then response to nitrogen and phosphorus might not be linear, but rather, addition above some certain level might only establish a plateau reflecting the other limitations.

The following definitions of the contrasts identify the elements of each comparison or contrast first in words, then in symbols. A positive contrast is assumed in each case.

Medium vs. River Water: Response with medium exceeds that with river water alone.

Medium vs. N3P3: Response with medium exceeds that with river water plus N3P3.

N (N vs. River Water): Response from adding N to river water exceeds the response with river water alone (average for 3 levels).

NP-P (N after P): Response from adding N and P to river water exceeds that from adding only P to river water (average for 3 levels).

P (P vs. River Water): Response from adding P to river water exceeds the response with river water alone (average for 3 levels).

NP-N (P after N): Response from adding P and N to river water exceeds that from adding only N to river water (average for 3 levels).

Interaction: Contrast when adding N and P together to river water exceeds the sum of the contrasts when adding N and P separately to river water (average for 3 levels) (this is a difference in contrasts and may be described several ways with perhaps the easiest to understand being that from the contrast when adding N and P together we subtract the sum of the contrast when adding N separately plus the contrast when adding P separately, where each of the three contrasts is measured as the excess of the response with the addition over the response with river water alone).

Calculation of contrasts from mean values for treatments (in symbols):

Medium vs. River Water: M - N0P0

Medium vs. N3P3: M - N3P3

N: (N1P0 + N2P0 + N3P0 - 3*N0P0)/3

NP-P: (N1P1 + N2P2 + N3P3 - N0P1 - N0P2 - N0P3)/3

P: (N0P1 + N0P2 + N0P3 - 3*N0P0)/3

NP-N: (N1P1 + N2P2 + N3P3 - N1P0 - N2P0 - N3P0)/3

Interaction: (N1P1 + N2P2 + N3P3 - N1P0 - N2P0 - N3P0 - N0P1 - N0P2 - N0P3 + 3*N0P0)/3.

Statistical analyses of a number of the parameters were carried out under logarithmic transformation both to stabilize the variance and to more nearly normalize the data. Logarithms to base 10 were used. As one consequence the tabulated mean values in some cases are stated both as arithmetic and as geometric means, the first because it is a more accustomed method of presentation for most readers and the second because the statistical analyses based on log-transformed data are best represented by the geometric mean. As a second consequence of use of the log transformation, the slope where a log-transformed variable is regressed on distance downstream (as in the covariance analyses used here) may be read in the antilog form as proportional change per unit distance.

Statistical analyses were carried out as two-way analyses of variance, simple regression, analysis of variance of factorial contrasts for the algal assays, and covariance analyses of a number of variables with reference to changes up and down stream. Standard procedures were employed for these analyses (Snedecor and Cochran 1967) being implemented through the general linear models procedure of SAS (Barr et al. 1976).

The analysis of covariance was used to explore the dynamics of these two streams; this analysis allowed an examination of changes both in space (up and down stream) and in time (from visit to visit). The covariable used was the approximate distance in kilometers from the origin of the stream for each of four subsites chosen so that the almost simultaneous records at each could be interpreted as following the water mass as it changed in moving down stream. The subsites were 20, 22, 24, and 25 for stream F-3 and 1, 3, 4, and 6, for stream P-10. The covariance analysis consisted of fitting three linear models in succession to the data for each stream (Snedecor and Cochran 1967). First it tested whether there was evidence of difference in slopes (of regressions on distance) among the data subsets for visits, second, whether the visit mean values differed when adjusted for the covariable, and third, whether a single regression fitted the mass of data significantly better than the mean value ignoring the covariable of distance. Carrying out the covariance analyses with log-transformed values of the dependent variable allowed a statement of slopes as proportional changes per kilometer of stream.

RESULTS

In total, 226 species of 108 genera of algae were recorded in 211 collections made at 12 subsites, 6 on each of the two streams, F-3 and P-10. The number of genera recorded per subsite visit averaged 12 and ranged from 3 to 27.

The taxonomic distribution of these species is shown in Table 35 along with the cell density (cells per ml) and species total volume (cubic microns per ml, or as biomass, 10^{-6} mg per liter) averaged over all collections. Table 36 summarizes this information and shows as proportions the distribution of species according to Class, with the contribution of each Class to the average total cell number and biomass per collection. The Cyanophyta dominated numerically (making up 57 percent of the cell number) while the Chrysophyta dominated in biomass (65 percent). The relative dominance pattern among algal divisions changed seasonally, however. In stream F-10, for example (Table 37) the Chrysophyta had the highest relative cell volume during cooler months while Cryptophyta were more dominant in the warmer months, with the other divisions dominant in the fall.

Most of the species were recorded only rarely. Of the 226 species (plus a group of unidentified spores counted as one "species") 85 (37 percent) were found in only a single collection and 175 (77 percent) in 10 collections or fewer. The most common species, Cryptomonas erosa was recorded in 162 collections, followed by the unidentified spores in 157 and Achnanthes sp in 155. Only 3 other species were recorded in more than half (106) of the collections; these were Nitzschia sp (134), Navicula sp (127) and Eunotia sp (107).

Most of the numbers and the biomass of these algal populations were accounted for by a small list of species. There were only 16 species each of which constituted one percent or more of cell numbers and there were only 16 species where each had one percent or more of the total biomass. Table 38 lists the 5 most numerous species (which constituted 50 percent of the total cell number) and the 5 species with the most biomass (these made up 48 percent of the total biomass). Oscillatoria subtillissima, a blue-green, had the highest total cell count, and Frustulia sp, a diatom, accounted for the largest fraction of the total cell volume. Two species were on both lists.

In cell volume these species ranged over 6 orders of magnitude, from Merismopedia tenuissima, a blue-green with an average volume of 3 cubic

TABLE 35. TAXONOMIC DISTRIBUTION OF ALGAL SPECIES ACCORDING TO DIVISION AND CLASS, AS RECORDED IN 211 COLLECTIONS IN STREAMS F-3 AND P-10, SHOWING FOR EACH SPECIES THE NUMBER OF COLLECTIONS IN WHICH RECORDED, THE MEAN CELL COUNT AND MEAN BIOMASS PER COLLECTION

Genus and Species	Times recorded	Mean cell count (cells/ml)	Mean biomass (10^{-6} mg/l)
DIVISION CYANOPHYTA, CLASS CYANOPHYCEAE			
Agmenellum quadriduplica	2	1.83	5.5
Anabaena circinalis	17	4.56	455.0
Anabaena wisconsinense	1	1.41	305.4
Anacystis cyanaea	2	5.44	91.2
Anacystis firma	7	16.09	289.5
Anacystis incerta	3	19.96	359.2
Aphanizomenon flos-aquae	2	1.23	1,401.0
Calothrix sp	1	7.18	776.1
Chroococcus limneticus	4	0.66	5.9
Coccochloris sp	1	0.01	0.1
Coccochloris stagnina	1	18.83	339.0
Coelosphaerium naegelianum	7	3.40	681.1
Gomphosphaeria lacustris	2	1.08	22.8
Hapalosiphon sp	1	0.06	5.7
Marssoniella elegans	1	1.51	16.6
Merismopedia punctata	2	4.18	87.6
Merismopedia tenuissima	1	1.85	5.6
Oscillatoria geminata	10	4.17	451.5
Oscillatoria sp	11	5.16	557.1
Oscillatoria subtilissima	2	202.74	21,896.2
Phormidium sp	54	43.43	738.5
Plectonema battersii	2	0.82	14.0
Raphidiopsis curvata	3	1.01	191.3
Rhabdoderma lineare	2	0.13	3.3
Spirulina laxa	1	0.52	31.9
Unknown	1	0.71	282.1

TABLE 35. (continued)

Genus and Species	Times recorded	Mean cell count (cells/ml)	Mean biomass (10^{-6} mg/l)
DIVISION CHLOROPHYTA, CLASS CHLOROPHYCEAE			
Ankistrodesmus contorta	1	0.01	0.5
Ankistrodesmus convolutus	11	0.29	13.5
Ankistrodesmus falcatus	5	0.10	1.4
Ankistrodesmus falcatus var. mirabilis	16	0.70	13.1
Ankistrodesmus quarternatus	1	0.03	2.3
Asterococcus limneticus	1	0.50	173.7
Carteria fritschii	7	0.09	118.7
Characium rostratum	2	0.02	5.4
Chlamydomonas botryopara	1	0.12	7.7
Chlamydomonas botrys	3	0.40	208.2
Chlamydomonas sp	102	5.95	3,103.1
Chlorogonium spirale	1	0.01	1.5
Closteriopsis longissima	8	0.12	100.0
Closterium peracerosum	1	0.08	858.8
Closterium dianea	5	0.41	2,758.3
Coccomonas orbicularis	10	0.64	263.3
Coccomonas sp	1	0.07	29.6
Coelastrum microporum	1	0.11	33.1
Cosmarium speciosum	1	0.04	83.6
Cosmocladium pusillum	1	0.34	140.1
Crucigenia crucifera	5	0.97	12.5
Crucigenia quadrata	3	0.14	4.0
Crucigenia sp	1	0.08	2.0
Crucigenia tetrapedia	10	1.18	28.1
Dictyosphaerium pulchellum	1	0.03	1.9
Euastrum affine	2	0.02	8.0
Eudorina elegans	1	0.46	32.4
Gloeocystis botryoides	1	0.15	39.2

TABLE 35. (continued)

Genus and Species	Times recorded	Mean cell count (cells/ml)	Mean biomass (10^{-6} mg/l)
Gloeocystis sp	1	0.06	14.8
Gloeocystis vesiculosa	1	0.06	14.3
Golenkinia radiata	1	0.06	41.6
Gonatozygon kinahana	1	0.01	38.0
Hyalotheca dissiliens	2	0.25	1,412.3
Kirchneriella bibrianum	2	0.05	2.6
Kirchneriella lunaris	4	0.41	23.0
Kirchneriella obesa	1	0.01	0.6
Mephrocytium agardhiamum	1	1.18	39.8
Monoraphidium contortum	8	0.17	8.3
Mougeotia sp	2	0.55	5,325.1
Nephrocytium agardhianum	1	5.22	177.4
Palmodictyon viride	3	8.88	266.3
Pandorina morum	7	6.64	1,135.0
Pediastrum tetras var. tetraodon	1	0.16	6.4
Scenedesmus acuminatus	1	0.02	3.4
Scenedesmus alternans	1	0.01	3.4
Scenedesmus bijuga	8	0.33	20.2
Scenedesmus denticulatus	3	0.11	6.8
Scenedesmus dimorphus	1	0.19	26.0
Scenedesmus ecornis	2	0.10	6.0
Scenedesmus quadricauda	12	0.92	117.4
Scenedesmus quadricauda var. alternans	2	0.06	3.2
Scenedesmus arcuatus	14	0.44	30.7
Selenastrum bibrianum	1	<0.01	0.3
Selenastrum westii	14	0.43	17.0
Staurastrum orbicularis	6	1.66	3,355.0
Staurastrum cerastes	11	0.12	464.4
Staurastrum turgescens	1	<0.01	88.9

TABLE 35. (continued)

Genus and Species	Times recorded	Mean cell count (cells/ml)	Mean biomass (10^{-6} mg/l)
Tetraedron sp	1	0.03	2.9
Tetrastrum glabrum	1	0.03	0.5
Tetrastrum staurogeniaforme	3	0.46	4.2
Treubaria crassispina	1	<0.01	1.2
Ulothrix sp	1	0.32	79.7
Westella botryoides	4	0.21	23.4
DIVISION CHRYSOPHYTA, CLASS BACILLARIOPHYCEAE			
Achnanthes deflexa	5	0.97	148.6
Achnanthes lanceolata	1	<0.01	2.1
Achnanthes lemmermanii	2	0.02	7.0
Achnanthes linearis	1	0.01	1.4
Achnanthes microcephala	1	0.05	7.6
Achnanthes minutissima	2	0.19	19.1
Achnanthes sp	155	10.62	4,202.5
Amphipleura sp	1	0.09	47.3
Amphora ovalis	1	<0.01	75.2
Amphora sp	9	0.20	988.0
Bacillaria paradoxa	1	<0.01	0.7
Caloneis alpestris	1	<0.01	13.0
Caloneis lewisii	4	0.03	47.8
Caloneis lewisii var. inflata	1	0.05	251.1
Ceratoneis arcus	1	0.08	269.5
Cocconeis sp	16	0.20	486.0
Cyclotella glomerata	3	0.26	8.7
Cyclotella meneghioriania	1	0.17	198.0
Cyclotella sp	12	0.73	23.9
Cymatopleura solea	1	0.02	85.8
Cymbella naviculiforma	1	0.09	676.8
Cymbella sp	46	0.76	490.6

TABLE 35. (continued)

Genus and Species	Times recorded	Mean cell count (cells/ml)	Mean biomass (10^{-6} mg/l)
Cymbella tumida	1	0.02	258.8
Cymbella ventricosa	16	0.89	419.4
Diatoma vulgare	17	1.47	1,107.5
Diploneis oblongella	1	0.01	20.5
Epithemia sp	2	0.10	72.6
Eunotia arcus	1	0.01	19.8
Eunotia exigua	13	1.34	453.0
Eunotia pectinalis	1	0.01	24.3
Eunotia pectinalis var. minor	1	0.10	157.8
Eunotia sp	107	6.02	8,819.5
Fragilaria sp	16	0.75	752.7
Frustulia rhomboides	10	0.15	2,176.5
Frustulia sp	47	0.76	77,007.0
Gomphonema acuminatum var. coronata	1	0.03	13.4
Gomphonema gracillima	1	0.17	71.8
Gomphonema olivaceum	21	1.76	734.7
Gomphonema parvulum	2	0.02	9.8
Gomphonema sp	29	1.43	3,100.7
Mastigloia elliptica var. danseii	1	0.01	7.1
Melosira distans	2	0.08	12.8
Melosira distans var. alpisena	3	0.09	9.5
Melosira granulata	5	0.14	87.3
Melosira granulata var. angustissima	1	0.04	9.0
Melosira italica	8	0.98	2,234.3
Melosira italica var. tenuissima	21	1.05	196.1
Melosira sp	1	0.69	893.1
Melosira varians	5	0.23	709.6
Meridion circulare	66	3.04	1,370.5
Meridion circulare var. constrictium	5	0.09	40.3

TABLE 35. (continued)

Genus and Species	Times recorded	Mean cell count (cells/ml)	Mean biomass (10^{-6} mg/l)
Microsiphona potomos	2	0.76	76.5
Navicula cryptocephala	1	0.08	40.6
Navicula graciloides	4	0.06	44.4
Navicula hambergii	1	<0.01	2.6
Navicula pupila	2	0.06	110.2
Navicula pupila var. rectiosa	2	0.05	56.1
Navicula rhynchocephala	2	0.18	394.1
Navicula sp	127	5.13	2,516.1
Navicula viridula	1	0.01	6.4
Neidium affine	9	0.34	1,508.8
Neidium sp	88	2.89	13,202.1
Nitzschia acicularis	13	0.46	189.9
Nitzschia filaformis	4	0.04	16.6
Nitzschia ignorata	4	0.04	178.0
Nitzschia linearis	1	0.03	11.1
Nitzschia palea	39	5.82	4,112.9
Nitzschia parvula	3	0.09	95.8
Nitzschia recta	3	0.14	57.1
Nitzschia sp	134	7.19	299.2
Nitzschia thermalis	10	0.20	207.0
Nitzschia thermalis var. minor	3	0.07	63.4
Pinnularia sp	49	1.98	8,735.0
Pinnularia subcapitata	2	0.18	905.7
Rhizosolenia eriensis	2	0.02	14.1
Stauroneis phoenicenter	6	0.26	2,836.1
Surirella ovata	2	0.01	35.7
Surirella sp	56	2.01	6,347.7
Synedra incisa	2	0.02	18.2
Synedra sp	23	0.55	1,672.0

TABLE 35. (continued)

Genus and Species	Times recorded	Mean cell count (cells/ml)	Mean biomass (10^{-6} mg/l)
Synedra ulna	25	2.54	8,904.7
Tabellaria fenestrata	1	0.01	15.8
Tabellaria sp	52	1.61	1,890.4
Unknown	44	8.22	10,028.5
DIVISION CHRYSOPHYTA, CLASS CHRYSOPHYCEAE			
Dinobryon acuminatum	1	0.01	5.9
Dinobryon ravaricum	2	0.15	70.1
Dinobryon divergens	1	0.01	1.2
Dinobryon sertularia	10	0.27	130.3
Dinobryon sp	5	0.06	25.4
Mallomonas sp	9	0.12	34.3
Mallomonas tonsurata	1	<0.01	2.0
Monochrysis aphanaster	1	0.23	158.6
Rhizochrysis sp	2	0.01	7.8
Stichococcus bacillaris	1	0.03	2.4
Synura caroliniana	5	7.92	3,681.4
Synura sp	43	5.91	2,736.1
Synura sphagnicola	10	0.30	234.6
Synura spinosa	24	23.99	53,917.7
Synura uvella	5	7.34	3,415.0
Tribonema sp	1	0.96	2,201.0
Unknown	1	0.16	62.8
DIVISION EUGLENOPHYTA, CLASS EUGLENOPHYCEAE			
Euglena acus	3	0.13	784.5
Euglena ehrenbergii	1	0.01	25.1
Euglena gracillima	1	0.04	117.5
Euglena proxima	5	0.26	953.7
Euglena sp	44	1.51	2,626.4

TABLE 35. (continued)

Genus and Species	Times recorded	Mean cell count (cells/ml)	Mean biomass (10^{-6} mg/l)
Lepocinclis ovum	1	0.11	107.6
Lepocinclis sp	8	0.41	144.9
Phacus acuminatus	1	0.01	35.3
Phacus longicauda	3	0.08	950.5
Phacus pleuronectes	2	0.13	1,437.2
Phacus sp	14	0.26	360.6
Phacus tortus	8	0.20	1,180.5
Strobomonas sp	12	0.57	5,762.3
Trachelomonas gibberosa	1	0.05	301.2
Trachelomonas hispida	9	0.36	1,513.3
Trachelomonas horrida	3	0.08	153.4
Trachelomonas oblonga	13	0.74	229.2
Trachelomonas robusta	22	0.43	1,543.4
Trachelomonas sp	41	0.98	2,846.2
Trachelomonas volvocina	5	0.11	56.2
DIVISION PYRRHOPHYTA, CLASS DINOPHYCEAE			
Ceratium hirundinella	1	0.01	1,572.0
Glenodinium penardiforme	1	0.01	233.7
Glenodinium sp	1	0.04	662.2
Gymnodinium neglectum	1	0.05	212.0
Peridinium inconspicuum	6	0.20	355.4
Peridinium sp	28	0.43	7,245.1
DIVISION CRYPTOPHYTA, CLASS CRYPTOPHYCEAE			
Chroomonas acuta	27	9.49	996.5
Chroomonas coerulea	4	0.82	58.8
Chroomonas sp	14	0.26	26.6
Cryptomonas erosa	162	16.57	11,585.7
Cryptomonas erosa var. reflexa	17	0.93	644.3

TABLE 35. (continued)

Genus and Species	Times recorded	Mean cell count (cells/ml)	Mean biomass (10^{-6} mg/l)
Cryptomonas ovata	77	4.74	10,684.6
Cryptomonas reflexa	7	0.19	135.9
Cryptomonas sp	34	1.14	513.2
Cyanomonas americana	16	0.34	228.9
DIVISION CHLOROMONADOPHYTA, CLASS CHLOROMONADOPHYCEAE			
Gonyostomum depressum	1	0.01	23.3
DIVISION UNKNOWN, CLASS UNKNOWN*			
Unknown	157	58.64	23,471.3

* Unidentifiable small green spheres, mostly spores, probably of numerous species.

TABLE 36. TAXONOMIC DISTRIBUTION OF ALGAL SPECIES COLLECTED IN THIS STUDY, SHOWING THE PROPORTION EACH CLASS CONSTITUTES OF THE TOTAL NUMBERS AND BIOMASS

Division and Class (common name)	Genera	Species	Proportion of total by numbers	Proportion of total by biomass
Cyanophyta, Cyanophyceae (blue-green algae)	20	26	0.566	0.079
Chlorophyta, Chlorophyceae (green algae)	36	63	0.069	0.056
Chrysophyta, Bacillariophyceae (diatoms)	31	84	0.125	0.469
Chrysophyta, Chrysophyceae (yellow-green algae)	8	17	0.077	0.180
Euglenophyta, Euglenophyceae (euglenoids)	5	20	0.010	0.057

TABLE 36. (continued)

Division and Class (common name)	Genera	Species	Proportion of total by numbers	Proportion of total by biomass
Pyrrhophyta, Dinophyceae (dinoflagellates)	4	6	0.001	0.028
Cryptophyta, Cryptophyceae (naked flagellates)	3	9	0.056	0.067
Chloromonadophyta, Chloromonadophyceae (chloromonads)	1	1	<0.001	<0.001
Unknown, Unknown*	-	-	0.095	0.063
Total	108	226		

* Unidentifiable small green spheres, mostly spores, probably of numerous species.

TABLE 37. RELATIVE CONCENTRATION OF ALGAL BIOMASS AMONG THE DIVISIONS CHRYSOPHYTA, CRYPTOPHYTA AND ALL OTHER DIVISIONS FOR STREAM P-10 THROUGHOUT THE STUDY

Visit no.	Date	Proportion of Biomass by Division Chrysophyta	Cryptophyta	Other Divisions
1	3 Dec 74	0.153	0.252	0.595
2	19 Dec 74	0.111	0.222	0.667
3	6 Jan 75	0.280	0.252	0.468
4	15 Jan 75	0.357	0.145	0.498
5	31 Jan 75	0.731	0.122	0.147
6	20 Feb 75	0.416	0.190	0.394
7	7 Mar 75	0.539	0.090	0.371
9	27 Mar 75	0.503	0.061	0.436
12	14 Apr 75	0.456	0.225	0.319

TABLE 37. (continued)

Visit no.	Date	Proportion of Biomass by Division Chrysophyta	 Cryptophyta	 Other Divisions
13	18 Apr 75	0.368	0.197	0.435
16	9 July 75	0.122	0.279	0.599
17	21 July 75	0.164	0.741	0.095
19	15 Aug 75	0.238	0.100	0.662
21	7 Sept 75	0.124	0.232	0.644
23	5 Oct 75	0.114	0.000	0.856
26	23 Nov 75	0.274	0.081	0.645
28	20 Dec 75	0.749	0.126	0.125
30	18 Jan 76	0.783	0.032	0.185
32	11 Feb 76	0.856	0.002	0.142
33	5 Mar 76	0.639	0.075	0.286

TABLE 38. THE 5 ALGAL SPECIES MOST ABUNDANT BY CELL NUMBER AND THE 5 MOST ABUNDANT BY BIOMASS IN THIS STUDY, SHOWING PROPORTION OF TOTAL CELL NUMBERS AND TOTAL BIOMASS ACCOUNTED FOR BY EACH OF THESE SPECIES

Species	Mean per sample		Species proportion of total		Common name
	cell number (cells/ml)	biomass (10^{-6} mg/l)	cell number	biomass	
Five highest by cell number					
Oscillatoria subtillissima	203	21,896	0.330	0.059	blue-green
Phormidium sp	43	738	0.070	0.002	blue-green
Synura spinosa	24	53,918	0.039	0.146	chrysophite
Anacystis incerta	20	359	0.032	0.001	blue-green

TABLE 38. (continued)

Species	Mean per sample cell number (cells/ml)	Mean per sample biomass (10^{-6} mg/l)	Species proportion of total cell number	Species proportion of total biomass	Common name
Coccochloris stagnina	19	339	0.031	0.001	blue-green
Total			0.502	0.209	
Five highest by biomass					
Frustulia sp	0.76	77,007	0.001	0.208	diatom
Synura spinosa	24	53,918	0.039	0.146	chrysophite
Oscillatoria subtillissima	203	21,896	0.330	0.059	blue-green
Neidium sp	2.9	13,202	0.005	0.036	diatom
Cryptomonas erosa	16	11,586	0.027	0.031	cryptophyte
Total			0.402	0.480	
Total of all species collected	615	369,716			

An important component of the algae was a complex of unidentifiable small green spheres, mostly spores, probably of numerous species; the entity would rank second in numbers and third in biomass, above.

microns, to *Ceratium hirundinella*, a dinoflagellate with a volume estimated as 110,657 cubic microns per cell. The distribution of species according to cell volume is shown in Table 39 both according to quartiles of numbers of species and by order of magnitude of cell volume. Species with small cell volume predominated, with half being of less than 500 cubic microns.

The total cell count (all species) averaged 615 over all 211 collections and ranged from 8 to 8,400 per ml. Total cell biomass averaged 0.37 and ranged from 0.01 to 17 mg per liter; 11 values exceeded 1 mg per liter. Using the data of Nichols (1976) the abundance of algae represented in these collections corresponded to an average chlorophyll *a* content of approximately 2 with a range of 0.04 to 80 micrograms per liter.

TABLE 39. DISTRIBUTION OF 227* ALGAL SPECIES ACCORDING TO MEAN CELL VOLUME, BY QUARTILE AND BY ORDER OF MAGNITUDE OF CELL VOLUME, SHOWING ALSO THE PROPORTIONAL DISTRIBUTION OF TOTAL CELL NUMBER AND TOTAL BIOMASS

	Number of species	Proportion of species	Volume range (cubic microns)	Proportion of algal cell numbers	Proportion of algal biomass
By quartiles of species					
1st quartile	56	0.247	3-102	0.250	0.010
2nd quartile	57	0.251	103-448	0.524	0.158
3rd quartile	57	0.251	450-1,764	0.141	0.177
4th quartile	57	0.251	1,785-110,567	0.085	0.655
By order of magnitude of cell volume					
	4	0.017	1-10	0.008	<0.001
	47	0.207	10-100	0.240	0.010
	98	0.432	100-1,000	0.633	0.260
	64	0.282	1,000-10,000	0.115	0.457
	12	0.053	10,000-100,000	0.003	0.061
	2	0.009	over 100,000	0.001	0.212

* Including as a "species" the group of unidentifiable spores.

The detailed quantitative aspects of the total algal community are presented for each of the two streams for a subset of data which includes all the visits when all of four selected subsites were represented on each stream. These subsites were selected to record a continuing flow of the same mass of water. For the piedmont stream F-3, these subsites were numbered 1, 3, 4, 6, proceeding downstream, with a tributary entering between 3 and 4. For coastal plain stream P-10, the subsites were numbered 20, 22, 24 and 25, proceeding downstream, with a tributary entering between 22 and 24.

Variability in time and in space are shown in tables of mean values for these two stream systems. For parameters of the algal populations and for most chemical parameters, each subsite mean was based on 19 visits for piedmont stream F-3 and on 13 visits for coastal plain stream P-10. In both streams, each visit mean was based upon the 4 subsite values. Both arithmetic and geometric means are presented.

Mean values showing spatial variation in flow and in parameters of the algal population are presented in Table 40 for stream F-3 and Table 41 for stream P-10. A two-way analysis of variance of log-transformed data was used to test differences between subsites in each stream for flow, concentration of cell number and biomass, and the measurements of diversity and evenness. In both streams, the subsites differed in flow in a highly significant manner, increasing downstream as should be expected. With cell number and biomass concentration, sites differed significantly in stream P-10, but not in stream F-3. For diversity and evenness there were no significant differences among sites in either stream. These same tables also show values for transport of algal numbers and biomass which generally follow those for flow, increasing downstream.

The same type of information is presented for 5 chemical parameters in Table 42 for stream F-3 and Table 43 for stream P-10. Again, analysis of variance tests were made for differences between subsites with reference to concentrations but not for transport. Statistically significant differences between subsites were found for nitrate nitrogen for both streams, for ammonia nitrogen for stream F-3, and for chloride in stream P-10. No significant differences were found in either stream for concentrations of Kjeldahl nitrogen or orthophosphate. In most but not all cases, transport increased downstream in the general pattern of flow.

Temporal variation among visit means is shown for piedmont stream F-3 in Tables 44 and 45 and for coastal plain stream P-10 in Tables 46 and 47 for algal numbers, biomass, and diversity, and for flow and concentration of nitrate nitrogen and chloride. Two-way analyses of variance showed that for all these variables in both streams there were statistically significant differences among mean values for visits, indicating synchronous changes in parameter values across the 4 subsites.

The occurrence of an algal bloom is an important aspect of temporal variation in biomass. According to one rule of thumb, a biomass of 10^6 cubic microns per ml (1 mg per liter, wet weight) is near the minimum level for a bloom. As mentioned above, in the total of 211 collections, there were 11 where the biomass exceeded 1 mg per liter and thus qualified as a bloom by this definition. Of these 11 samples, 6 were collected on 2 visits to stream P-10 (on 23 November 1975 and on 5 March 1976) and 5 were collected on 1 visit to stream F-3 (on 9 March 1976). The subsets of data for each stream where 4 subsites were represented at each visit provide information for approximating the expected frequency of bloom conditions in the streams. Values (in $\log_{10}$ units) for mean biomass concentration and the standard error of visit mean values (each based upon 4 subsites) for stream F-3 are -1.0566 ± 0.3962, and for stream P-10, -0.7232 ± 0.4703 (values derived from covariance analysis of biomass data, detailed below). Assuming a log normal distribution of the values of biomass concentration, these values for mean and standard error allow estimation of the frequency with which visit geometric means (each for 4 subsites) will exceed the criterion for a bloom (1 mg per liter). In these terms, these data suggest that with stream F-3 the criterion will be exceeded about one-half of one percent of the time, while with stream P-10 blooms will be present about 6 percent of the time. Empirically, the subsets of data show one instance in 19 visits for stream F-3 and two cases in 13 visits for stream P-10. Similar calculations of the expectation of single values exceeding the 1 mg per liter criterion yield about 2 percent for stream F-3 and about 10 percent for stream P-10. The reasoning leading to these approximations makes no allowance for possible serial correlations and is thus based upon use of a sampling interval similar to that used here.

TABLE 40. SPATIAL VARIATION OF FLOW AND ALGAL PARAMETERS IN PIEDMONT STREAM F-3; ARITHMETIC AND GEOMETRIC MEAN VALUES AND RESULTS OF TESTS OF THE STATISTICAL SIGNIFICANCE OF SUBSITE DIFFERENCES FOR SELECTED VARIABLES

Parameter	Type of mean	Means for 19 visits to subsites				Statistical significance of subsite differences
		20	22	24	25	
Distance from origin (km)		1.2	8.2	8.4	10.2	
Flow (m^3/sec)	arith.	0.132	0.451	0.774	0.886	
	geom.	0.041	0.129	0.281	0.290	**
Cell number						
concentration (cells/ml)	arith.	535	362	362	359	
	geom.	146	129	152	154	ns
transport (10^9 cells/d)	arith.	4,933	32,108	26,790	58,174	
	geom.	519	1,434	3,696	3,872	
Biomass						
concentration (mg/l)	arith.	0.186	0.160	0.195	0.245	
	geom.	0.087	0.084	0.091	0.089	ns
transport (kg/d)	arith.	2.63	12.09	21.61	40.64	
	geom.	0.31	0.93	2.23	2.24	
Diversity	arith.	2.40	2.56	2.30	2.29	ns

TABLE 40. (continued)

Parameter	Type of mean	Means for 19 visits to subsites 20	22	24	25	Statistical significance of subsite differences
Evenness	arith.	0.749	0.768	0.673	0.705	ns

** Statistical significance: $p \leq 0.01$.

ns Statistical significance: $p > 0.05$.

TABLE 41. SPATIAL VARIATION OF FLOW AND ALGAL PARAMETERS IN COASTAL PLAIN STREAM P-10; ARITHMETIC AND GEOMETRIC MEAN VALUES AND RESULTS OF TESTS OF THE STATISTICAL SIGNIFICANCE OF SUBSITE DIFFERENCES FOR SELECTED VARIABLES

Parameter	Type of mean	Means of 13 visits to subsites 1	3	4	6	Statistical significance of subsite differences
Distance from origin (km)		0.2	2.8	3.0	6.0	
Flow (m^3/sec)	arith.	0.010	0.013	0.024	0.104	**
	geom.	0.002	0.005	0.012	0.072	
Cell number						
concentration (cells/ml)	arith.	424	3,033	272	204	*
	geom.	222	232	144	95	
transport (10^9 cells/d)	arith.	191	848	333	983	
	geom.	49	95	152	594	
Biomass						
concentration (mg/l)	arith.	1.65	0.52	0.24	0.82	**
	geom.	0.33	0.22	0.16	0.11	
transport (kg/d)	arith.	0.39	0.26	0.34	3.64	
	geom.	0.073	0.089	0.169	0.694	
Diversity	arith.	2.75	2.79	2.92	2.35	ns
Evenness	arith.	0.766	0.759	0.795	0.736	ns

* Statistical significance: $0.01 < p \leq 0.05$.
** Statistical significance: $p \leq 0.01$.
ns Statistical significance: $p > 0.05$.

TABLE 42. SPATIAL VARIATION OF CHEMICAL PARAMETERS OF PIEDMONT STREAM F-3; ARITHMETIC AND GEOMETRIC MEAN VALUES AND RESULTS OF TESTS OF THE STATISTICAL SIGNIFICANCE OF SUBSITE DIFFERENCES FOR SELECTED VARIABLES

Parameter	Type of mean	Means of 19 visits to subsites†				Statistical significance of subsite differences
		20	22	24	25	
Distance from origin (km)		1.2	8.2	8.4	10.2	
Nitrate nitrogen						
concentration (ppm)	arith.	0.0632	0.0589	0.0553	0.0547	
	geom.	0.0478	0.0359	0.0351	0.0356	*
transport (kg/d)	arith.	0.57	1.70	3.10	3.02	
	geom.	0.17	0.41	0.87	0.91	
Kjeldahl nitrogen						
concentration (ppm)	arith.	1.24	0.99	1.06	1.07	
	geom.	0.74	0.64	0.74	0.91	ns
transport (kg/d)	arith.	14.0	41.3	61.5	87.8	
	geom.	2.0	5.2	14.6	22.8	
Ammonia nitrogen						
concentration (ppm)	arith.	0.0800	0.0143	0.0128	0.0157	
	geom.	0.0184	0.0055	0.0040	0.0056	*
transport (kg/d)	arith.	1.56	1.49	1.79	2.99	
	geom.	0.35	0.18	0.08	0.79	
Orthophosphate						
concentration (ppm)	arith.	0.0637	0.0637	0.0842	0.0616	
	geom.	0.0311	0.0355	0.0275	0.0218	ns
transport (kg/d)	arith.	0.49	1.56	2.37	2.81	
	geom.	0.08	0.36	0.42	0.31	
Chloride						
concentration (ppm)	arith.	3.99	3.34	4.46	5.95	
	geom.	3.38	3.17	3.73	3.65	ns
transport (kg/d)	arith.	65	104	215	213	
	geom.	12	35	91	92	

* Statistical significance: $0.01 < p \leq 0.05$.
ns Statistical significance: $p > 0.05$.
† Exception: ammonia had 9 visits.

TABLE 43. SPATIAL VARIATION OF CHEMICAL PARAMETERS IN COASTAL PLAIN STREAM P-10; ARITHMETIC AND GEOMETRIC MEAN VALUES AND RESULTS OF TESTS OF THE STATISTICAL SIGNIFICANCE OF SUBSITE DIFFERENCES FOR SELECTED VARIABLES

Parameter	Type of mean	Means of 13 visits to subsites† 1	3	4	6	Statistical significance of subsite differences
Distance from origin (km)		0.2	2.8	3.0	6.0	
Nitrate nitrogen						
concentration (ppm)	arith.	0.293	0.430	0.450	0.174	
	geom.	0.137	0.277	0.334	0.115	*
transport (kg/d)	arith.	0.32	0.36	0.74	2.11	
	geom.	0.02	0.11	0.35	0.72	
Kjeldahl nitrogen						
concentration (ppm)	arith.	1.39	1.30	1.14	1.04	
	geom.	0.96	0.91	0.96	0.62	ns
transport (kg/d)	arith.	0.68	1.32	2.44	9.27	
	geom.	0.13	0.29	1.01	3.49	
Ammonia nitrogen						
concentration (ppm)	arith.	0.180	0.268	0.188	0.436	
	geom.	0.012	0.035	0.025	0.067	ns
transport (kg/d)	arith.	0.002	0.096	0.073	1.719	
	geom.	0.001	0.017	0.022	0.340	
Orthophosphate						
concentration (ppm)	arith.	0.106	0.108	0.132	0.131	
	geom.	0.092	0.097	0.120	0.097	ns
transport (kg/d)	arith.	0.06	0.11	0.30	1.27	
	geom.	0.02	0.04	0.13	0.61	
Chloride						
concentration (ppm)	arith.	11.2	12.1	11.8	8.1	
	geom.	9.7	10.9	10.8	7.9	**
transport (kg/d)	arith.	6.9	8.9	16.6	64.2	
	geom.	2.0	4.5	11.3	49.7	

* Statistical significance: $0.01 < p \leq 0.05$.

** Statistical significance: $p \leq 0.01$.

ns Statistical significance: $p > 0.05$.

† Exception: ammonia had 6 visits.

TABLE 44. TEMPORAL VARIATION OF ALGAL NUMBERS, BIOMASS, AND DIVERSITY IN PIEDMONT STREAM F-3; ARITHMETIC AND GEOMETRIC MEANS FOR 13 VISITS, EACH TO 4 SUBSITES

Visit	Date	Algal nos. (cells/ml)		Algal biomass (mg/l)		Algal diversity
		arith. mean	geom. mean	arith. mean	geom. mean	arith. mean
1	25 Nov 74	50	34	0.050	0.036	1.49
2	10 Dec 74	552	293	0.080	0.080	1.77
4	23 Jan 75	140	102	0.059	0.041	1.81
5	26 Jan 75	52	49	0.048	0.046	2.79
6	11 Feb 75	65	62	0.085	0.074	3.04
7	28 Feb 75	111	110	0.118	0.099	3.22
9	1 Apr 75	254	229	0.222	0.206	2.88
10	8 Apr 75	193	158	0.116	0.101	2.50
12	10 May 75	88	80	0.067	0.064	2.86
14	11 Jun 75	55	52	0.036	0.032	2.69
15	27 Jun 75	20	17	0.025	0.022	1.82
18	25 Jul 75	182	146	0.273	0.127	2.45
20	4 Sep 75	421	401	0.164	0.089	1.90
21	15 Sep 75	1,707	644	0.253	0.161	2.25
26	27 Nov 75	783	668	0.318	0.272	0.48
27	9 Dec 75	259	244	0.152	0.148	3.42
30	14 Jan 76	60	56	0.038	0.030	3.19
31	26 Jan 76	400	190	0.180	0.092	2.05
34	9 Mar 76	2,297	2,064	1.445	1.063	2.75

TABLE 45. TEMPORAL VARIATION OF FLOW AND CONCENTRATION OF NITRATE NITROGEN AND CHLORIDE IN PIEDMONT STREAM F-3; ARITHMETIC AND GEOMETRIC MEANS FOR 13 VISITS, EACH TO 4 SUBSITES

Visit	Date	Flow (m^3/sec)		Nitrate nitrogen concentration (ppm)		Chloride concentration (ppm)	
		arith. mean	geom. mean	arith. mean	geom. mean	arith. mean	geom. mean
1	25 Nov 74	0.05	0.04	0.002	0.002	3.6	3.5
2	10 Dec 74	0.22	0.17	0.035	0.034	3.8	3.8
4	23 Jan 75	0.34	0.29	0.065	0.063	3.2	3.2
5	26 Jan 75	2.00	1.34	0.052	0.052	2.9	2.9
6	11 Feb 75	0.31	0.26	0.058	0.054	3.0	3.0
7	28 Feb 75	0.25	0.17	0.020	0.017	2.8	2.7
9	1 Apr 75	0.34	0.24	0.018	0.016	2.3	2.2
10	8 Apr 75	0.15	0.10	0.012	0.012	2.5	2.5
12	10 May 75	0.11	0.08	0.052	0.052	2.4	2.4
14	11 Jun 75	0.02	0.01	0.148	0.146	8.5	6.4
15	27 Jun 75	0.01	0.01	0.238	0.237	17.7	9.2
18	25 Jul 75	0.25	0.21	0.085	0.085	3.0	3.0
20	4 Sep 75	0.02	0.02	0.038	0.037	2.9	2.9
21	15 Sep 75	0.03	0.02	0.052	0.048	4.2	4.0
26	27 Nov 75	0.16	0.13	0.038	0.037	4.2	4.1
27	9 Dec 75	0.89	0.67	0.042	0.042	3.5	3.5
30	14 Jan 76	0.30	0.24	0.048	0.047	3.9	3.7
31	26 Jan 76	3.54	2.93	0.025	0.024	2.2	2.2
34	9 Mar 76	1.67	1.36	0.075	0.074	7.7	5.6

TABLE 46. TEMPORAL VARIATION OF ALGAL NUMBERS, BIOMASS, AND DIVERSITY IN COASTAL PLAIN STREAM P-10; ARITHMETIC AND GEOMETRIC MEANS FOR 13 VISITS, EACH TO 4 SUBSITES

Visit	Date	Algal nos. (cells/ml) arith. mean	Algal nos. (cells/ml) geom. mean	Algal biomass (mg/l) arith. mean	Algal biomass (mg/l) geom. mean	Algal diversity arith. mean
2	19 Dec 74	120	112	0.134	0.118	2.19
3	6 Jan 75	184	172	0.203	0.197	2.43
4	15 Jan 75	109	97	0.096	0.088	3.25
5	31 Jan 75	124	88	0.184	0.124	2.94
7	7 Mar 75	326	300	0.321	0.292	3.27
9	27 Mar 75	130	108	0.089	0.080	2.97
12	14 Apr 75	88	86	0.131	0.118	3.27
13	18 Apr 75	133	103	0.229	0.136	3.16
17	21 Jul 75	143	135	0.159	0.152	1.22
26	23 Nov 75	10,096	2,622	1.830	1.287	1.64
28	20 Dec 75	50	41	0.125	0.081	3.03
30	18 Jan 76	103	93	0.106	0.098	3.41
33	5 Mar 76	1,180	894	6.887	2.650	2.35

TABLE 47. TEMPORAL VARIATION OF FLOW AND CONCENTRATION OF NITRATE NITROGEN AND CHLORIDE IN COASTAL PLAIN STREAM P-10; ARITHMETIC AND GEOMETRIC MEANS FOR 13 VISITS, EACH TO 4 SUBSITES

Visit	Date	Flow (m³/sec) arith. mean	Flow (m³/sec) geom. mean	Nitrate nitrogen concentration (ppm) arith. mean	Nitrate nitrogen concentration (ppm) geom. mean	Chloride concentration (ppm) arith. mean	Chloride concentration (ppm) geom. mean
2	19 Dec 74	0.014	0.008	0.462	0.384	15.9	15.2
3	6 Jan 75	0.040	0.026	0.582	0.582	9.6	9.5

TABLE 47. (continued)

Visit	Date	Flow (m^3/sec) arith. mean	Flow (m^3/sec) geom. mean	Nitrate nitrogen concentration (ppm) arith. mean	Nitrate nitrogen concentration (ppm) geom. mean	Chloride concentration (ppm) arith. mean	Chloride concentration (ppm) geom. mean
4	15 Jan 75	0.175	0.122	0.245	0.242	6.1	6.0
5	31 Jan 75	0.045	0.033	0.285	0.273	6.1	6.1
7	7 Mar 75	0.037	0.022	0.412	0.370	8.6	8.5
9	27 Mar 75	0.042	0.028	0.250	0.219	5.5	5.5
12	14 Apr 75	0.009	0.001	0.110	0.083	19.1	17.9
13	18 Apr 75	0.007	0.002	0.320	0.190	14.7	14.3
17	21 Jul 75	0.037	0.003	0.285	0.252	6.3	6.3
26	23 Nov 75	0.006	0.002	0.010	0.010	16.0	15.4
28	20 Dec 75	0.022	0.010	0.660	0.565	9.8	9.7
30	18 Jan 76	0.043	0.027	0.388	0.362	8.7	8.6
33	5 Mar 76	0.015	0.006	0.368	0.062	14.0	13.5

The percentage that the algae carried of the total organic carbon, total nitrogen and total phosphorus in the two streams was approximated for a number of samples; mean values are shown in Table 48. These results

TABLE 48. ALGAE-CARRIED NUTRIENTS; CALCULATED CONTENT OF ALGAL BIOMASS AS MEAN AND MAXIMUM PERCENTAGE OF THE TOTAL ORGANIC CARBON, TOTAL NITROGEN, AND TOTAL PHOSPHORUS DETERMINED BY CHEMICAL ANALYSIS OF WATER SAMPLES FROM TWO STREAMS

Site	Minimum sample size	Algal content as percent of total: Organic carbon mean	Organic carbon max.	Total nitrogen mean	Total nitrogen max.	Total phosphorus mean	Total phosphorus max.
Coastal plain stream P-10	56	1.1	15	3.6	78	3.9	79
Piedmont stream F-3	90	0.3	2	0.6	55	1.0	9

indicate that on the average the algae contained only small percentages of the nutrients available in the stream. On the other hand, there were 10 values in all exceeding 10 percent (including the maximum values in the table); these reflect the rare occurrence of high biomass values.

The standing crop of numbers of algae observed in samples from these two streams was compared in an approximate way with the maximum standing crop obtained with algal assay of the same water (using a single test species in the laboratory as described later). The comparison was made by calculating the ratio: observed standing crop in numbers divided by the assay maximum standing crop (calculated as numbers in the manner described in the methods section). These ratios were extremely low; for piedmont stream F-3 they averaged 0.0002 (maximum 0.002) and for coastal plain stream P-10 they averaged 0.0005 (maximum 0.009). These values indicate that in these streams under natural conditions the standing crop lies far below the potential (usually by a factor of several thousand) inasfar as this may be judged by such an approximate comparison to the single laboratory test species.

Simple regression analysis was used to explore the relationship between the algae and environmental parameters. A separate line was fitted for each of 11 subsites for regressions of algal parameters (log-transformed cell numbers and biomass, untransformed diversity and evenness) on nitrate nitrogen, Kjeldahl nitrogen, total phosphorus, chloride, temperature C, pH, day length and dissolved oxygen as determined for the water samples. An analysis was carried out for data from each of subsites 1, 2, 3, 4, and 6 of stream P-10 and from subsites 20, 22, 23, 24, 25, 28 of stream F-3; each regression was based upon the records of from 9 to 16 visits. Thus 344 analyses were examined (subsite 28 lacked complete data on pH and dissolved oxygen). Results of these regression analyses are presented in Table 49 by listing those subsites where a statistically significant ($p \leq 0.05$) regression was found. This table shows that there were scattered occurrences of significant relationships (in total, 21 out of the 344; one would expect about 17 on a basis of chance alone). All that may be said for this regression analysis is that it provides no evidence of consistent relationships between the algal and chemical parameters measured; one must recall, however, that sample sizes were low and the ranges of the independent variables were restricted.

Regression analysis was also used to test for a possible temporal relationship in variation in algal numbers and diversity in the two streams using the mean values listed in Tables 44 and 46. In both streams the apparent relationship was negative, indicating a lower diversity with higher algal population but in neither stream was the relationship significant at the 0.05 level in spite of the coincidence in coastal stream P-10 of very high algal numbers and a low diversity value.

The two stream systems were compared directly on the basis of algal numbers, biomass, diversity and evenness, using an analysis of variance

TABLE 49. TESTS FOR REGRESSION OF ALGAL PARAMETERS (CELL NUMBER, BIOMASS, DIVERSITY, EVENNESS) ON SELECTED ENVIRONMENTAL PARAMETERS (CALCULATED INDEPENDENTLY AT 11 SUBSITES ON TWO STREAMS*) LISTING SUBSITES WHERE REGRESSION WAS STATISTICALLY SIGNIFICANT ($p \leq 0.05$)

Independent variable	Dependent variable			
	Algal cell number	Algal biomass	Diversity	Evenness
Nitrate nitrogen	2, 6	2, 6	2	2
Kjeldahl nitrogen	24			25
Total phosphate	25, 28	28		
Chloride	2, 25	2		
Temperature C		25		
Day length				
pH	22	22	24, 25	25
Dissolved oxygen			25	

* A total of 344 regressions were calculated; the 21 "significant" is close to the 17.2 expected by chance.

of data from 4-week sampling periods when both streams were represented. Only for biomass was the difference between the two streams statistically significant ($p < 0.001$) and here there was also a highly significant ($p < 0.001$) interaction of stream and period. This means that while stream P-10 generally exceeded F-3 in biomass, the difference was of a different order in different periods or might be reversed in some. In all tests, period differences were highly significant indicating that all four parameters fluctuated in time more or less in synchrony in the two streams, subject to the significant interaction of stream and period with numbers, biomass, and diversity.

The analysis of covariance was used to examine the changes in flow and algal and chemical parameters in space (up and down stream) and in time (from visit to visit). Overall mean values have been presented above to show the spatial variation in flow and algal and chemical parameters in Tables 40, 41, 42, and 43 with temporal variation illustrated for part of the variables in Tables 44, 45, 46, and 47.

Results of the covariance analysis for piedmont stream F-3 are shown in Table 50 and for coastal plain stream P-10 are shown in Table 51.

TABLE 50. RELATIONSHIP OF FLOW, ALGAL, AND CHEMICAL PARAMETERS TO DISTANCE DOWNSTREAM FOR PIEDMONT STREAM F-3, BASED UPON COVARIANCE ANALYSIS OF DATA FROM 4 SUBSITES AND 19 VISITS (EXCEPT FOR AMMONIA WITH 7 VISITS); DATA LOG-TRANSFORMED (EXCEPT FOR DIVERSITY AND EVENNESS)

Parameter	Statistical significance of differences among visits:		Common slope fitted through visit means	Antilog of common slope
	slopes	means		
Flow	ns	**	0.0948**	1.24
Algal parameters				
Numbers				
concentration	ns	**	0.0007ns	1.00
transport	ns	**	0.0955**	1.24
Biomass				
concentration	**	**	0.0011ns	1.00
transport	ns	**	0.0959**	1.25
Diversity	ns	**	-0.0064ns	0.98
Evenness	ns	**	-0.0047ns	0.99
Chemical parameters				
Nitrate nitrogen				
concentration	**	**	-0.0158**	0.96
transport	ns	**	0.0780**	1.20
Kjeldahl nitrogen				
concentration	ns	**	0.0045ns	1.01
transport	ns	**	0.1079**	1.28
Ammonia nitrogen				
concentration	**	**	-0.0680**	0.86
transport	ns	**	0.0064ns	1.01
Orthophosphate				
concentration	ns	**	-0.0106ns	1.02
transport	ns	**	0.0805	1.20
Chloride				
concentration (log)	ns	**	0.0028ns	1.01
transport (log)	ns	**	0.0976**	1.25

* Statistical significance: $0.01 < p \le 0.05$.

** Statistical significance: $p < 0.01$.

ns Statistical significance: $p > 0.05$.

TABLE 51. RELATIONSHIP OF FLOW, ALGAL, AND CHEMICAL PARAMETERS TO DISTANCE DOWNSTREAM FOR COASTAL PLAIN STREAM P-10, BASED UPON COVARIANCE ANALYSIS OF DATA FROM 4 SUBSITES WITH 13 VISITS (EXCEPT FOR AMMONIA WITH 5 VISITS); DATA LOG-TRANSFORMED (EXCEPT FOR DIVERSITY AND EVENNESS)

Parameter	Statistical significance of differences among visits:		Common slope fitted through visit means	Antilog of common slope
	slopes	means		
Flow	ns	**	0.2553**	1.80
Algal parameters				
Numbers				
concentration	ns	**	-0.0658**	0.86
transport	ns	**	0.1895**	1.55
Biomass				
concentration	ns	**	-0.0821**	0.83
transport	ns	**	0.1732**	1.49
Diversity	ns	**	-0.0710ns	0.85
Evenness	ns	**	-0.0052ns	0.99
Chemical parameters				
Nitrate nitrogen				
concentration	ns	**	-0.0175ns	0.96
transport	ns	**	0.2618**	1.83
Kjeldahl nitrogen				
concentration	*	**	-0.0328ns	0.93
transport	*	*	0.2474**	1.77
Ammonia nitrogen				
concentration	**	**	0.1263*	1.34
transport	ns	**	0.4519**	2.83
Orthophosphate				
concentration	ns	**	0.0040ns	1.01
transport	*	**	0.2654**	1.84
Chloride				
concentration	ns	**	-0.0159**	0.96
transport	ns	**	0.2455**	1.76

* Statistical significance: $0.01 < p \leq 0.05$.

** Statistical significance: $p \leq 0.01$.

ns Statistical significance: $p > 0.05$.

First, for each parameter the table shows the results of testing differences among slopes for the different visits. Second, the table indicates the statistical significance of differences among visit mean values. Third is stated the slope for a set of lines fitted, one through each visit mean, with common slope (a value which has meaning only if there is no evidence of difference between slopes for the different visits) and the indication of whether this common slope fits significantly better than the general regression fitted to the entire set of data. Finally, each table shows the antilog of the common slope value; this shows in the form of a multiplier the proportional change accompanied by moving a kilometer downstream. Again, this value has meaning only if there is no evidence of difference among visits with regard to slope.

There were significant differences among visit means for all parameters examined by covariance in the two streams. In most cases there was no evidence that the sets of data for the different means differed in slope; exceptions to this generality were with Kjeldahl nitrogen concentration and transport, ammonia nitrogen concentration and orthophosphate transport in stream P-10 and biomass concentration, nitrate nitrogen concentration and ammonia nitrogen concentration in stream F-3. This means that, aside from the exceptions, the values for the parameters varied proportionately from visit to visit, maintaining the same relationship up and down stream.

Flow increased in going downstream, with the common slope equivalent to a gain of 24 percent per kilometer in stream F-3 and 80 percent per kilometer in stream P-10. In concentration of algal numbers and biomass and the chemical constituents, the only significant changes in stream F-3 were with nitrate nitrogen and ammonia nitrogen, both of which decreased significantly at average rates of 4 percent and 14 percent per kilometer respectively. In stream P-10, however, concentration of algal numbers decreased at the rate of 14 percent per kilometer, biomass concentration at the rate of 17 percent per kilometer, and chloride concentration at the rate of 4 percent per kilometer while in this stream ammonia nitrogen increased at the rate of 34 percent per kilometer. Other changes in both streams were nonsignificant.

Values for transport of algae and chemicals generally followed the trend of flow, increasing downstream (in most cases significantly) but at a rate reflecting both the changes in flow and in concentration. For example, in stream P-10 where algal biomass concentration decreased when going downstream at the rate of 17 percent per kilometer while the flow was increasing at the rate of 80 percent per kilometer, the transport increased at the rate of 49 percent. With ammonia nitrogen, in stream F-3 the concentration decreased significantly and with an increase in flow, resulted in a nonsignificant change in transport, while in stream P-10 with ammonia nitrogen concentration increasing at a rate of 34 percent per kilometer and the flow increasing at the rate of 80 percent, the combined effect was an increase of 183 percent per kilometer. But recall that sample sizes were small with ammonia.

Results from the algal assays comprise a large mass of data in spite of the fact that sampling was on a reduced schedule, both in time and in space and part of the results had to be discarded. For each assay there were 10 treatment levels with every lot of bottles having its own medium control. Each assay level was carried out with three (or two) replicated bottles. Results are presented here for 83 assays; several from subsites visited on an irregular basis were not used.

Results from the algal assays are summarized in Tables 52, 53, 54, and 55 which show the statistical results in terms of whether the effects were statistically significant. Mean values are not shown except for the 10 mean values for several selected assays (Table 56) presented as examples of statistically significant interactions.

Tables 52, 53, 54, and 55 record the statistical significance of results of five factorial contrasts; a negative sign signals that results of the particular contrast were negative. In these tables, N and P indicate the mean effect of adding nitrogen or phosphorus to the water being assayed, the contrast being between water with the three levels of nutrient added and the natural water with no addition. Two other contrasts, NP-P and NP-N, test for the effect of adding one nutrient to water already containing the other. The contrast labeled INT tests whether addition of both nutrients together produced a greater effect than that calculated as the sum of the effects of adding them separately. Table 56 presents several examples of assay mean values selected to illustrate an interaction in this context, and incidentally, cases of negative effects. Greater detail on these contrasts has been presented in the section on methods.

With each lot of bottles run through the laboratory assay, a replicated set of bottles was used with the laboratory medium and the test alga as a control. Two statistical comparisons were made in each analysis, contrasting the results for the medium with those for the unenhanced natural water, and with those for natural water plus the highest levels of nitrogen and phosphorus added (N3P3). These contrasts were positive with one exception; in stream P-10 visit 16 subsite 6 the relationship was reversed, probably indicating a doubtful laboratory result. Except for this one, most differences were highly significant ($p \leq 0.01$); there were seven exceptions with one difference significant at the 0.05 level and the others nonsignificant. These results confirmed laboratory control of the process.

In the broad view, using the 0.01 level for statistical significance, about half (86) of the 166 assay results tabulated in these tables indicate a significant effect from addition of nitrogen and in 44 cases there is evidence of an effect with neither nitrogen nor phosphorus. Interpretation of the remaining values is less clear, with 32 indicating a significant effect with both nutrients although in 16 of these cases one or more negative values obscure the interpretation. A significant effect was associated with addition of phosphorus in four cases, in three of which the effect had negative values. Thus, over the whole, about

TABLE 52. ALGAL ASSAY -- RESULTS OF STATISTICAL ANALYSIS FOR MAXIMUM STANDING CROP FOR PIEDMONT STREAM F-3; N (OR P) REPRESENTS THE MEAN EFFECT OF NITROGEN (OR PHOSPHORUS) ADDITION, NP-P (OR NP-N) THE MEAN ADDED EFFECT OF NITROGEN AND PHOSPHORUS TOGETHER OVER PHOSPHORUS (OR NITROGEN) ALONE, AND INT REPRESENTS INTERACTION, OR THE EXCESS EFFECT OF ADDING NITROGEN AND PHOSPHORUS TOGETHER OVER THE SUM OF THE SEPARATE EFFECTS

Subsite	N	NP-P	NP-N	P	INT	Subsite	N	NP-P	NP-N	P	INT
Visit 18	25 July 1975					Visit 26	27 November 1975				
20	**	**	**	-ns	**	20	ns	ns	-ns	-ns	ns
22	**	**	**	-ns	**	22	ns	*	ns	-ns	ns
23	**	**	**	-ns	**	23	ns	ns	-ns	ns	-ns
24	**	**	**	-ns	**	24	ns	ns	-ns	ns	-ns
25	**	**	**	-ns	**	25	ns	ns	-ns	-ns	ns
28	**	**	*	ns	-ns	28	ns	*	ns	-ns	ns
Visit 20	4 September 1975					Visit 27	9 December 1975				
20	**	**	ns	-ns	ns	20	ns	*	-ns	-ns	-ns
22	**	**	*	ns	ns	22	**	**	-ns	-ns	-ns
23	**	**	ns	ns	-ns	23	**	**	-ns	ns	-ns
24	**	**	ns	-ns	ns	24	ns	**	-ns	-*	-ns
25	**	**	-**	ns	-*	25	**	**	-ns	-ns	ns
28	**	**	-ns	-ns	ns	28	ns	*	-ns	-ns	ns
Visit 21	15 September 1975					Visit 30	14 January 1976				
20	**	**	-ns	**	-**	20	ns	ns	-ns	ns	-ns
22	**	**	ns	-ns	*	22	*	**	ns	-ns	ns
23	**	ns	-ns	ns	-ns	23	**	**	ns	-ns	ns
24	**	**	ns	ns	-ns	24	**	**	ns	-ns	ns
25	**	**	-*	ns	-*	25	*	**	ns	ns	ns
28	**	**	-**	**	-**	28					
Visit 23	14 October 1975					Visit 31	26 January 1976				
20	**	**	ns	ns	-ns	20	-ns	ns	-ns	-ns	ns
22	**	-*	-**	**	-**	22	**	**	ns	ns	-ns
23	**	*	-**	-ns	-*	23	**	**	-ns	ns	-ns
24	*	**	-ns	-ns	ns	24	**	**	-ns	-ns	ns

TABLE 52. (continued)

Subsite	N	NP-P	NP-N	P	INT	Subsite	N	NP-P	NP-N	P	INT
25	ns	**	**	-ns	*	25	**	**	-ns	ns	-ns
28	ns	-ns	-**	-ns	ns	28	ns	**	ns	-*	*
Visit 34	9 March 1976										
20	**	**	ns	-ns	ns						
22	**	**	ns	-ns	ns						
23	**	**	-ns	-ns	-ns						
24	**	**	ns	-ns	ns						
25	**	**	**	-ns	ns						
28											

* Statistically significant, $0.01 < p < 0.05$.

** Statistically significant, $p \leq 0.01$.

- Negative sign indicates a negative effect (a reduction).

TABLE 53. ALGAL ASSAY -- RESULTS OF STATISTICAL ANALYSIS FOR MAXIMUM STANDING CROP FOR COASTAL PLAINS STREAM P-10; N (OR P) REPRESENTS THE MEAN EFFECT OF NITROGEN (OR PHOSPHORUS) ADDITION, NP-P (OR NP-N) THE MEAN ADDED EFFECT OF NITROGEN AND PHOSPHORUS TOGETHER OVER PHOSPHORUS (OR NITROGEN) ALONE, AND INT REPRESENTS INTERACTION, OR THE EXCESS EFFECT OF ADDING NITROGEN AND PHOSPHORUS TOGETHER OVER THE SUM OF THE SEPARATE EFFECTS

Subsite	N	NP-P	NP-N	P	INT	Subsite	N	NP-P	NP-N	P	INT
Visit 16	9 July 1975					Visit 26	23 November 1975				
1						1	-ns	**	*	-**	**
2	*	**	ns	ns	-ns	2	ns	ns	ns	ns	-ns
3						3	ns	*	ns	ns	-ns
4	**	**	ns	ns	ns	4	ns	*	ns	-ns	ns
6	**	**	-ns	-**	*	6	ns	*	ns	ns	ns
Visit 19	15 August 1975					Visit 28	20 December 1975				
1						1	ns	**	*	-ns	ns
2						2	-ns	ns	-ns	-*	ns
3						3	ns	**	*	-ns	ns

TABLE 53. (continued)

Subsite	N	NP-P	NP-N	P	INT	Subsite	N	NP-P	NP-N	P	INT
4						4	-ns	ns	ns	-ns	ns
6	**	**	**	**	ns	6	**	**	-ns	ns	-ns
Visit 21	7 September 1975					Visit 30	18 January 1976				
1						1	ns	**	*	-ns	ns
2						2	*	**	ns	ns	-ns
3						3	ns	*	-ns	-ns	-ns
4						4	ns	ns	ns	ns	-ns
6	**	**	ns	-ns	ns	6	**	**	ns	ns	ns
Visit 23	5 October 1975					Visit 32	11 February 1976				
1						1	ns	**	**	ns	**
2						2	**	**	ns	ns	ns
3						3	**	**	-ns	-*	ns
4						4	**	**	-ns	ns	-ns
6	*	ns	ns	-ns	-ns	6	**	**	-*	-ns	-ns
Visit 33	5 March 1976										
1	**	**	ns	-ns	ns						
2	**	**	ns	-ns	ns						
3	**	**	*	ns	ns						
4	**	**	-ns	-ns	ns						
6	**	**	-ns	-ns	ns						

* Statistically significant, $0.01 < p < 0.05$.

** Statistically significant, $p \leq 0.01$.

- Negative sign indicates a negative effect (a reduction).

TABLE 54. ALGAL ASSAY -- RESULTS OF STATISTICAL ANALYSIS FOR MAXIMUM SPECIFIC GROWTH RATE FOR PIEDMONT STREAM F-3; N (OR P) REPRESENTS THE MEAN EFFECT OF NITROGEN (OR PHOSPHORUS) ADDITION, NP-P (OR NP-N) THE MEAN ADDED EFFECT OF NITROGEN AND PHOSPHORUS TOGETHER OVER PHOSPHORUS (OR NITROGEN) ALONE, AND INT REPRESENTS INTERACTION, OR THE EXCESS EFFECT OF ADDING NITROGEN AND PHOSPHORUS TOGETHER OVER THE SUM OF THE SEPARATE EFFECTS

Subsite	N	NP-P	NP-N	P	INT	Subsite	N	NP-P	NP-N	P	INT
Visit 18	25 July 1975					Visit 26	27 November 1975				
20	**	**	-ns	ns	-ns	20	**	**	ns	*	-ns
22	**	**	*	ns	ns	22	*	**	-ns	-ns	-ns
23	**	**	ns	-*	*	23	*	**	-ns	-ns	ns
24	**	**	**	ns	ns	24	ns	**	ns	-*	*
25	**	**	**	ns	**	25	ns	**	ns	-**	**
28	**	**	ns	ns	ns	28	**	ns	-ns	*	-*
Visit 20	4 September 1975					Visit 27	9 December 1975				
20	**	**	-**	-**	ns	20	ns	ns	-ns	-ns	-ns
22	ns	**	**	-ns	**	22	ns	*	ns	ns	ns
23	**	ns	-ns	**	-**	23	-ns	**	ns	-*	**
24	**	**	-ns	-**	**	24	ns	*	-ns	-ns	ns
25	ns	**	ns	-**	**	25	ns	**	*	-ns	ns
28	**	**	-ns	-*	ns	28	-ns	ns	-ns	-ns	ns
Visit 21	15 September 1975					Visit 30	14 January 1976				
20	**	**	ns	*	-ns	20	**	**	**	-**	**
22	**	**	ns	-ns	*	22	**	**	ns	-ns	*
23	**	**	-*	ns	-ns	23	**	**	ns	-ns	ns
24	**	**	ns	-ns	ns	24	**	**	-*	**	-**
25	**	**	**	*	-ns	25	**	**	ns	-*	*
28	**	**	ns	-ns	ns	28					
Visit 23	14 October 1975					Visit 31	26 January 1976				
20	ns	*	-ns	-ns	-ns	20	-ns	ns	ns	-ns	ns
22	ns	**	-ns	-**	*	22	**	**	-ns	ns	-ns
23	-ns	**	-ns	-**	*	23	-ns	ns	ns	-*	ns
24	-ns	-ns	-ns	ns	-ns	24	**	-ns	-ns	*	-*
25	**	ns	-**	-ns	-**	25	ns	**	-ns	-*	ns
28	**	**	-**	-*	ns	28	ns	-ns	-ns	ns	-ns

TABLE 54. (continued)

Subsite	N	NP-P	NP-N	P	INT	Subsite	N	NP-P	NP-N	P	INT
Visit 34	9 March 1976										
20	*	-ns	-ns	ns	-*						
22	**	**	-ns	-ns	ns						
23	**	**	-ns	-ns	ns						
24	**	**	ns	-ns	ns						
25	*	**	*	-ns	*						
28											

* Statistically significant, 0.01 < p < 0.05.

** Statistically significant, p ≤ 0.01.

- Negative sign indicates a negative effect (a reduction).

TABLE 55. ALGAL ASSAY -- RESULTS OF STATISTICAL ANALYSIS FOR MAXIMUM SPECIFIC GROWTH RATE FOR COASTAL PLAINS STREAM P-10; N (OR P) REPRESENTS THE MEAN EFFECT OF NITROGEN (OR PHOSPHORUS) ADDITION, NP-P (OR NP-N) THE MEAN ADDED EFFECT OF NITROGEN AND PHOSPHORUS TOGETHER OVER PHOSPHORUS (OR NITROGEN) ALONE, AND INT REPRESENTS INTERACTION, OR THE EXCESS EFFECT OF ADDING NITROGEN AND PHOSPHORUS TOGETHER OVER THE SUM OF THE SEPARATE EFFECTS

Subsite	N	NP-P	NP-N	P	INT	Subsite	N	NP-P	NP-N	P	INT
Visit 16	9 July 1975					Visit 26	23 November 1975				
1						1	ns	ns	ns	ns	-ns
2	-ns	ns	ns	-ns	ns	2	ns	-ns	-*	ns	-ns
3						3	ns	ns	-ns	-ns	-ns
4	ns	*	ns	ns	ns	4	ns	**	-ns	ns	ns
6	-*	ns	-ns	-**	*	6	*	-ns	-**	ns	-*
Visit 19	15 August 1975					Visit 28	20 December 1975				
1						1	ns	**	*	-ns	ns
2						2	ns	-ns	*	ns	-ns
3						3	-ns	*	ns	-ns	ns
4						4	-ns	ns	**	ns	ns
6	**	ns	-ns	**	-**	6	ns	ns	ns	ns	-ns

TABLE 55. (continued)

Subsite	N	NP-P	NP-N	P	INT	Subsite	N	NP-P	NP-N	P	INT
Visit 21	7 September 1975					Visit 30	18 January 1976				
1						1	ns	ns	ns	ns	-ns
2						2	ns	-ns	-ns	*	-*
3						3	ns	**	ns	-ns	ns
4						4	ns	-ns	ns	ns	-ns
6	**	**	-ns	ns	-*	6	**	**	-ns	*	-*
Visit 23	5 October 1975					Visit 32	11 February 1976				
1						1	**	**	ns	*	-ns
2						2	*	-ns	-ns	ns	-ns
3						3	**	-**	-*	**	-**
4						4	**	*	-ns	-ns	-ns
6	**	**	-ns	-ns	ns	6	ns	**	**	-ns	*
Visit 33	5 March 1976										
1	*	ns	-*	ns	-ns						
2	ns	**	ns	-ns	ns						
3	-ns	ns	ns	-ns	ns						
4	ns	-ns	ns	ns	-ns						
6	**	**	ns	ns	-ns						

* Statistically significant, $0.01 < p < 0.05$.

** Statistically significant, $p \leq 0.01$.

- Negative sign indicates a negative effect (a reduction).

TABLE 56. ALGAL ASSAY -- SELECTED EXAMPLES FROM STREAMS F-3 AND P-10 WITH STATISTICALLY SIGNIFICANT ($p \leq 0.01$) INTERACTIONS, SHOWING MEANS FOR THE 10 TREATMENTS FOR MAXIMUM STANDING CROP AND MAXIMUM SPECIFIC GROWTH RATE

Form used to display mean values in this table				1/Standing crop; P-10 visit 26; subsite 1; interaction = 0.113			
NOP3			N3P3	0.153			0.285
NOP2		N2P2		0.154		0.197	
NOP1	N1P1			0.154	0.194		

TABLE 56. (continued)

NOPO	N1PO	N2PO	N3PO	0.226	0.156	0.164	0.232
Standing crop; M-3 visit 18; subsite 23; interaction = 0.040				[2] Standing crop; M-3 visit 23; subsite 22; interaction = -0.044			
0.020			0.186	0.191			0.195
0.019		0.077		0.188		0.179	
0.017	0.029			0.185	0.168		
0.023	0.032	0.062	0.092	0.169	0.197	0.205	0.215
Growth rate; P-10 visit 19; subsite 6; interaction = -0.374				[3] Growth rate; M-3 visit 26; subsite 25; interaction = 0.177			
1.064			1.419	0.588			0.847
0.980		1.059		0.530		0.679	
1.057	0.971			0.485	0.666		
0.728	1.115	1.182	1.357	0.702	0.634	0.706	0.822

[1] Also illustrates negative contrast; P = -0.072.

[2] Also illustrates negative contrast; NP-N = -0.025.

[3] Also illustrates negative contrast; P = -0.167.

half the tests showed a clear effect from addition of nitrogen and about a quarter of the tests no effect from either nutrient.

Negative values were obtained in a number of the assays of stream water. Most of these were nonsignificant and thus by definition were within the range to be expected from the variability of the measurements, but several were highly significant ($p \leq 0.01$). The incidence of these significant negative values is shown as follows:

Parameter	Stream	Number of assays	N	NP-P	NP-N	P	INT
Standing crop	F-3	52	0	0	5	0	2
	P-10	31	0	0	0	2	0
Growth rate	F-3	52	0	0	3	7	3
	P-10	31	0	1	1	1	2

Each of these cases was examined for unusual data such as extremely high values for NOPO. Three instances of these significant negative contrasts are included in Table 56 among the five examples of significant interactions. Of the 20 cases of negative effects (excluding interactions) all but one involved the addition of phosphorus, either alone or after nitrogen. The exception involved the addition of nitrogen after phosphorus.

In the 166 analyses there were 22 highly significant interactions, meaning that the effect of phosphorus and nitrogen together was either significantly greater or significantly less than the effect expected from action of the nutrients separately. Table 56 exhibits five examples of interactions selected to demonstrate the effect (calculation of an interaction is explained in the methods section).

DISCUSSION

Working so far up into the head waters of these two small streams with waters that had been exposed to biological exploitation for so short a time, we may ask, first, why we found as many algae as we did, and second, why we did not find more. Generality of our conclusions must be limited because we worked with only two streams, one in the Piedmont and the other in the Coastal Plain.

We found a fairly large and diversified flora, dominated by a few species in numbers and biomass. Most species were rare, with over a third appearing in only a single collection; this implies that further collecting and examination of collections would record many more species. Generally, algal abundance was very low compared to the assay-tested capability of the water to produce a standing crop but occasionally the abundance rose into the range of a possible bloom. Algal biomass was typically one to two orders of magnitude less than that reported by Stanley and Hobbie (1977) for the lower Chowan River, suggesting that realization of some of the available growth potential may be a partial explanation for the nuisance algal blooms reported there (Bond et al. n.d.).

In one of these streams the number of algae per volume of water decreased as the water moved downstream but at the same time with increasing flow the transport of algae increased, implying that there were substantial additions to the population mass between stations even though population density was diluted. In the other stream total algal transport also increased but there was no evidence of change in population density. Thus the processes of population increase differed somewhat between streams.

An important question is the source of these population increases, a source capable of providing the pulse for a bloom. Although this study provides no detailed answer, it is clear that only a few sources are possible. The source most often credited for stream phytoplankton is washout from periphyton living on the bottom of the stream; Swanson and Bachman (1976) found a relationship between the export of phytoplankton and the area of streambed above the sampling point. Another source of phytoplankton in these small drainage basins may be drainage from standing water in ponds in fields and woods. A third possible source is from runoff over the land surface where algae may grow under suitable conditions. A final possible source of algal increase is reproduction of cells carried by the flowing water, although the short residence times in these streams prevent this from being an important factor. These observations argue against significant growth of planktonic algae; thus the algae observed in the stream must originate from other environments. Similar conclusions have been drawn in recent reviews of stream ecology (Whitton 1975, Hynes 1970). The observations also suggest that considerable algal growth may occur downstream when conditions become favorable.

Algal populations fluctuated in time in a manner at least consistent with the notion that the changes were of the same proportion in the various parts of the stream examined. Some of the chemical parameters behaved in the same manner, others did not and ammonia differed in behavior between the two streams. The simple idea of dilution by ground water, at first thought to be a possible explanation (Hayne et al. 1977) cannot explain the changes; probably the interaction of a series of processes is involved. It is not possible to distinguish between such influences with the present data.

Except during the rare bloom conditions, the algae contained only small percentages of the nitrogen, phosphorus and organic carbon transported by the streams. Studies of the nearby Pamlico River support this conclusion (Harris and Hobbie 1974, Hobbie et al. 1972), and data from Nichols (1976) and Nichols and MacCrimmon (1975) on the Holland River also indicate that only 5-6 percent of the total nitrogen and total phosphorus are present in algal biomass.

Conceptually, there can be a very large number of environmental variables with an influence on growth of phytoplankton, but it has been found that in a given situation only a few are important (e.g., Walsh 1971). We found that in both streams inorganic nitrogen and phosphorus were usually available for algal growth, averaging 0.38 mg per liter nitrate plus ammonia and 0.14 mg per liter inorganic phosphorus. These values greatly exceed the concentrations generally recognized as limiting uptake of nutrients, i.e., 0.03 mg per liter nitrogen and 0.06 mg per liter phosphorus (Eppley et al. 1969; MacIsaac and Dugdale 1969; Fuhs et al. 1972). Because nitrogen and phosphorus were present in concentrations sufficient to saturate uptake kinetics these nutrients could not be limiting growth. Instead, we suggest that stream flushing rate and amount of available light may have been important.

If the flushing rate is high enough, the phytoplankters will be washed through a system before the population can reproduce appreciably (Lund 1965). As flushing rate decreases and residence rate increases, more algal growth can occur in a reach of given length and thus, with other factors equal we may expect more phytoplankton in more slowly moving streams with the potential for visible bloom directly proportional to the residence time. Both of these streams had high rates of flushing.

The availability of enough light for photosynthesis is a second environmental variable that may be important for controlling algal growth in streams. Some streams flow under dense forest cover; suspended sediment and water color limit light penetration in some. In any stream, algal cells experience exponentially decreasing light with depth and growth will depend upon the integrated light exposure of cells as they rise and fall in the turbulence of flowing waters. The concept of critical mixing depth has been developed to describe this situation in oceanic systems (Yentsch 1975); this is the depth of mixing at which the net growth is zero because integrated photosynthesis (a function of depth) is balanced by respiration (independent of depth). Something similar must apply also in flowing streams.

The dynamics of flow, algal populations and chemical parameters were studied here using probability sampling in time and the analysis of covariance. Results suggest that this is a promising technique for the study of small streams. The linear regression model used here provides only an approximation to the measurement of change over a distance of several kilometers. Probably change is not a smooth process with a continuous rate for all variables as might be implied by the linear model. The general idea of applying probability sampling to this problem need not be confined to the linear regression model used here; it might well be simplified to the comparison of successive pairs of points in a more detailed analysis of dynamics.

We cannot generalize from these results to processes in small streams in general, except to point out that these two streams differ in some characteristics. Therefore, if the dynamics of small streams are to be studied by choosing a random sample of streams and studying changes in selected reaches, the sample sizes must be large enough to deal with the variability we have demonstrated.

The algal assays provided two kinds of evidence about the water quality of these small drainage basins. First, the populations of the test algae developed in the unspiked natural water provided a measure of the potential growth possible in this water, and furnished a basis for comparison with the ambient algal populations present in the same water. If the growth potential of these particular waters is the only point of interest, a much simplified bottle assay method could be devised to use only the unfortified natural waters to approximate the maximum standing crop for comparison with the standing crop of indigenous algae observed in the stream. Such a technique would provide estimates both of the standing crop achieved in the stream, and the approximate fraction this comprises of the maximum possible.

The second kind of information from the algal assays relates to potential growth limitation and at best has meaning for interpreting field data as applying to the hypothesized continuation of algal growth in exactly these same waters until nitrogen or phosphorus or both have been so reduced that low availability of the elements inhibits further growth. In the small drainage basins where this work was done such hypothetical conditions would occur far downstream, perhaps in the main portion of the river or in the estuary. The further assumption that these waters would be unaltered in their travels except by the uptake of nutrients by the algae further removes the interpretation of results from direct application to the small streams. With these limitations in mind, let us examine the results of the algal assays made here.

In the total of 166 values (83 assays, each calculated as maximum standing crop and the maximum specific growth rate) three patterns of results predominate, ignoring the presence or absence of a significant* interaction. The most frequent pattern (61/166) was for the effect of N and of NP-P to both be significant with neither of the phosphorus effects significant; this clearly indicated potential limitation by nitrogen. The second pattern in frequency (44/166) was non-significance in all four effects (N, NP-P, NP-N, P) indicating no potential limitation by any of these elements and thus probably limitation by some other entity. The third most frequent pattern (21/166) was for a non-significant effect of N, a significant effect of NP-P, and lack of significance for the two phosphorus effects. This may be classified as limitation by nitrogen and near limitation by phosphorus with the two nutrients only slightly unbalanced with respect to the requirements of the test species. Addition of nitrogen under this condition may have provided a slight increase in response but at a level unidentifiable as statistically significant; the relative abundance of nitrogen and phosphorus then shifted so that phosphorus became limiting with the result that when it was added with nitrogen present the response was clearly identifiable. This pattern is classified here as representing potential nitrogen limitation. In the remaining cases (40/166) some of the results are confusing and difficult to interpret; in about half the presence of negative effects provided evidence of occasional limitation through toxicity or growth suppression by nutrients or interacting factors. There was a single clear case of potential phosphorus limitation.

The two criteria of maximum specific growth rate and maximum standing crop were used in each assay to estimate the potential nutrient limitation. Under the 0.01 level of statistical significance used here, conclusions would be identical as to limiting nutrients in about half the assays and would disagree somewhat in the rest, although some of the disagreement may be seen as one or the other assay being more sensitive in the particular instance. Reviewing Tables 52, 53, 54, and 55 it may be seen that consistency of results seems to have been more a matter of the particular stream rather than whether standing crop or growth was used as the criterion, with more variable and erratic results in coastal plain stream P-10 under both criteria. This apparent difference may be a matter of stream heterogeneity. Thus these empirical results do not confirm the theoretical argument that standing crop should be a more satisfactory criterion than growth rate. It is interesting, however, that the range of increase of growth rate seems to have fallen generally within the predicted two-fold limitation.

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* In this paragraph, the term "significant" refers to statistical significance with $p \leq 0.01$.

In comparing results of samples taken from different points on the same stream during a single day there is a surprising amount of apparent disagreement as to potential nutrient limitation. We suspect that the apparent differences are reliable (although they were not tested statistically) because the method seemed to provide reasonably good precision within any one assay, that is, it was usually able to detect statistically significant differences with the modest level of replication used. The differences within streams on the same day, which were more apparent in stream P-10, may represent unexpected heterogeneity in the water of a single stream.

In summary of the algal assay method as used to appraise potential nutrient limitation, we found it provided apparently reliable information for a single assay while results were somewhat inconsistent for assays of water taken from different parts of the same stream on the same day. It is possible that the precision of the method has allowed the detection of unsuspected heterogeneity in flowing streams, and if this is true, then the apparent potential nutrient limitation, as determined from a single water sample, may not be a reliable indicator for an entire stream, even a small one. Further, the nature of this variation in small streams in space and time must be studied in greater detail. But whatever the variation, the concept of potential limitation by nutrients as determined for algae in such small streams, seems to apply to a hypothetical condition far downstream and under the unrealistic assumption that the nature of the waters will not be changed in moving there.

SECTION 7

BIOCHEMICAL OXYGEN DEMAND STUDIES

Samples for biochemical oxygen demand (BOD) tests were collected during the period from November 11, 1974 through July 21, 1975. The samples were collected from the F3 and P10 sites. These sites were F3K, F3M, F3A, F3W, F3X, P10A, P10B, P10K, P10W, and P10Y. The verification numbers were respectively 20, 22, 23, 24, 25, 1, 2, 3, 4, and 6. For each sample the following information was determined:

1. Five day BOD
2. Ultimate BOD
3. Oxygen uptake rate

This data was determined for the samples at three temperatures, 10 °C, 20 °C and 30 °C, and for duplicate sets of samples, one set containing an inhibitor to prevent nitrification and a second set without inhibitor.

The data was entered in the main data set using the following data set name arrangement. BOD data names are seven characters long. The first three are BOD. The fourth character will be a "5" if the value is a five-day reading or an "L" if the value is the ultimate calculated value. The fifth character will be an "I" if the sample contained a nitrification inhibitor or a "U" if no inhibitor was added. The sixth and seventh characters indicate the temperature at which the sample was run, 10 °C, 20 °C, or 30 °C. Thus, "BODLI20" is the ultimate calculated value for an inhibited BOD sample run at 20 °C.

The oxygen uptake rate data set names consist of five characters. The first two, "KE" indicate that the rate was calculated using log base e. The third and fourth indicate temperature and the fifth indicates if an inhibitor was used. Thus "KEIOU" is the data set name for oxygen uptake rates determined for uninhibited samples at 10 °C.

TESTING PROCEDURES

The BOD was run using the membrane electrode method. A YSI (Yellow Springs Instruments) membrane electrode was chosen due to ease of operation and availability. To insure accuracy and reliability, the electrode technique was tested against the standard Winkler-azide modification, a wet chemical test for determining dissolved oxygen, outlined in Standard Methods for the Examination of Water and Wastewater (APHA, 1971). Electrodes, calibrated daily by the Winkler-azide modification, never varied by more than two-tenths of one part per million of dissolved oxygen from the chemical method (Figure 16.

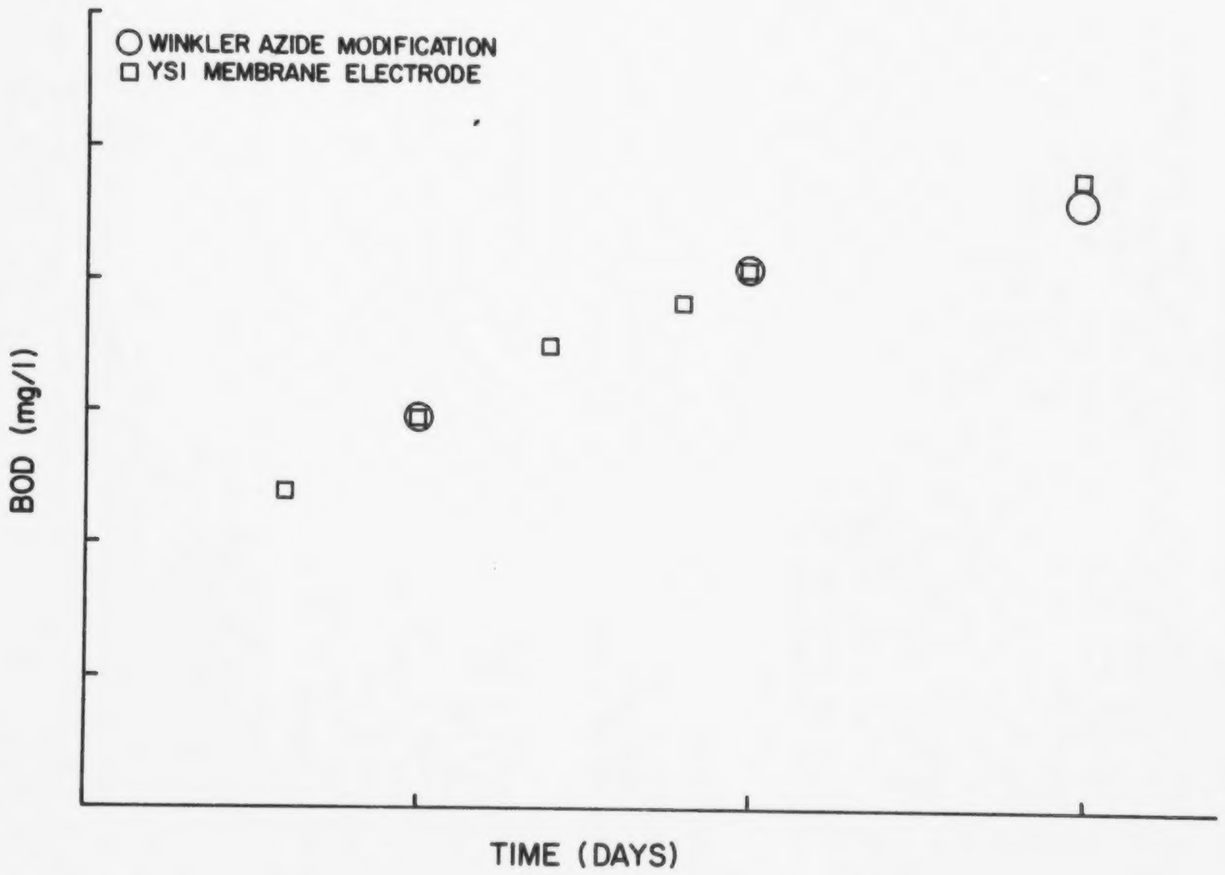

Figure 16. Biochemical oxygen demand comparison at various times for the winkler azide modification vs. YSI membrane electrode method.

The samples were run at three different temperatures and checked for dissolved oxygen concentration approximately every other day by the electrode method. In order to reduce the relative errors, duplicates were set up at each temperature: 10 °C, 20 °C, and 30 °C. Testing ten or more times in a twenty-day period provided a complete sequence of data.

The samples were collected and delivered to the Sanitary Engineering Laboratories at North Carolina State University a day or more after the actual sampling. Preservation was accomplished by "icing" the samples. Samples were run both with and without nitrification suppressor. The effects of several nitrification suppressors were evaluated. The inhibitor marketed by the Hach Company, No. 2533, proved to be the most effective suppressor of nitrogenous oxygen demand. The Hach inhibitor was also tested for carbonaceous demand and inhibition of cabonaceous demand. To evaluate the Hach inhibitor, a solution containing a small BOD and no ammonia was prepared by distillation, ion-exchange, and carbon absorption. Three BOD test sets were prepared using this solution. The first set contained only the solution, the second had the normal dose of Hach inhibitor added to the solution, and the third set contained an inorganic ion-exchange media, permutit, to insure no nitrification. The result showed no measurable differences in oxygen uptake between the three sets; thus, verifying the Hach inhibitor as solely a nitrification suppressor.

Analysis and Results

The discussion in this section will be confined to the values observed at 20 °C. As expected, the values found at 10 °C were lower than those found at 20 °C and those at 30 °C was higher. The same patterns were found at each temperature.

The ultimate BOD values found during this study were generally low, with the highest being 14.0 mg/l for samples without nitrification inhibitors and 13.2 mg/l with the inhibitors added. The minimum values were 0.65 mg/l and 0.55 mg/l respectively. The lower values are questionable, however, as the test requires that at least two mg/l of oxygen be used and these low tests did not use anywhere near this amount. The uninhibited values were, as expected, in general larger than the inhibited values. Very few BOD values were observed in excess of 10 mg/l.

The oxygen uptake rates ranged from less than 0.01 per day to 0.20 per day. Differences between the rates found for the uninhibited and inhibited samples could not be discerned immediately.

Trends could not be readily observed due to the short-time period over which the data was collected. However, it appears that the BOD values are greater during the summer than during the winter. The overall low values of BOD and oxygen uptake rates indicate the material causing the BOD was relatively stable before entering the streams. This was probably due to the fact that a large majority of the samples were collected during low flow periods and thus any materials entering the streams and contributing to BOD were relatively stale and thus stable.

An attempt was made to use the QUAL II model for these stream sections which were sampled for BOD and oxygen uptake rates. However, due to the low oxygen uptake rates and short-stream sections sampled the model could not be used effectively.

The data were then analyzed using the general linear models (GLM) procedure of the SAS system. The first series of tests examined whether there was a linear regression of BOD on chemical oxygen demand (COD) and of BOD on total organic carbon (TOC). Both the uninhibited ultimate BOD and the ultimate inhibited BOD were used.

This analysis indicated a statistically significant (P = 0.025 or less, see Table 57) linear regression on both COD and TOC for both inhibited and uninhibited BOD. However, the low values of R-square and the high coefficients of variation for all tests suggest that the correlation between these variables is of little practical significance.

The BOD data was also analyzed to see if there were consistent differences between sampling sites and between visits using the SAS procedure GLM for a two-way analysis of variance. The BOD again was the dependent variable with site (verficiation) and visit used as classes. The model appeared to have a reasonable fit with all values of R-square greater than 0.4; however, the values found for the coefficients of variation were also large (all greater than 45 percent), indicating a scattering of the data (Table 58).

An examination of the F-test data for the model indicates that differences in BOD values were detected with all models having F-values with probabilities of finding larger values of F less than 0.015. The analysis indicated statistically significant differences in BOD among visits (across all sites), but no significant differences among sites (across all visits).

TABLE 57. RELATIONSHIP OF BOD TO COD AND BOD TO TOC

Variable					
Dependent	Independent	F value	a greater F value	R-square	Coefficient of variation
BODL120	CODC	5.25	0.0251	0.072	84.16
BODLU20	CODC	12.13	0.0008	0.1425	72.83
BODL120	TOCC	14.10	0.0003	0.1531	75.25
BODLU20	TOCC	20.63	0.0001	0.1972	66.13

TABLE 58. ANALYSIS OF BOD VARIATION

Dependent Variable	F	PR>F	R-square	Coefficient of variation (%)	Source			
					Verif		Visit	
					F	PR>F	F	PR>F
BODL120	2.05	0.0142	0.473	70.71	1.12	0.3611	1.93	0.0466
BODLU20	2.42	0.0029	0.487	62.01	1.44	0.1780	2.76	0.0038
BOD5120	2.05	0.0009	0.412	147.5	0.72	0.8196	2.41	0.0012
BOD5U20	3.19	0.0001	0.524	114.14	0.74	0.7983	4.16	0.0001
BODG120	3.79	0.0001	0.6228	52.92	1.22	0.2988	4.05	0.0001
BODGU20	2.63	0.0012	0.509	45.662	1.08	0.3893	3.38	0.0006

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APPENDIX: PHYSICO-CHEMICAL PARAMETER VALUES FOR ALL 30 STATIONS SAMPLED

All values are in mg/L except TEMP - ^{0}C,
COND - µmhos/cm, pH - pH units, and FLOW - m^3/second

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
Station 1					
DO	37	7.96	1.6	14.7	3.41
TEMP	40	14.1	2	26	7.1
COND	38	70.2	20	152	35.6
pH	28	5.55	4.6	6.9	0.62
FLOW	50	0.021	0	0.70	0.098
COD	23	45.3	20	119	21.7
TOC	23	16.7	3	57	10.8
TP	35	0.216	0.05	0.79	0.174
NH_3-N	7	0.129	<0.01	0.86	0.323
NO_3-N	35	0.260	<0.01	1.55	0.300
TKN	35	1.638	<0.04	7.35	1.458
Cl	35	11.86	2.8	39.0	9.24
SS	12	54.7	8	237	65.4
Station 2					
DO	38	9.29	4.3	16.7	2.93
TEMP	40	13.3	2	24	6.2
COND	38	58.9	20	110	19.5
pH	28	5.65	4.6	6.7	0.57
FLOW	50	0.0090	0	0.12	0.021
COD	25	31.9	12	103	10.7
TOC	26	12.8	2	46	8.6
TP	38	0.199	0.06	0.75	0.177
NH_3-N	8	0.016	<0.01	0.07	0.024
NO_3-N	39	0.364	<0.01	1.07	0.281
TKN	38	1.380	0.38	3.27	0.730
Cl	39	10.66	2.2	21.2	4.73
SS	14	22.8	4	61	18.6
Station 3					
DO	35	9.52	3.1	18.0	3.10
TEMP	37	13.4	2	24	6.5
COND	35	64.6	25	154	29.5
pH	28	5.62	4.4	6.7	0.63
FLOW	51	0.014	0	0.314	0.046

APPENDIX (continued)

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
COD	24	35.0	12	111	20.4
TOC	25	13.8	2	53	10.2
TP	34	0.184	0.04	0.86	0.170
NH_3-N	8	0.196	<0.01	1.15	0.391
NO_3-N	34	0.398	0.01	1.36	0.373
TKN	34	1.694	<0.04	8.54	1.509
Cl	34	12.65	2.2	58.6	10.09
SS	13	23.4	6	50	13.6

Station 4

DO	43	8.59	0.5	17.2	3.42
TEMP	45	14.2	2	24	6.6
COND	43	66.9	25	200	31.3
pH	34	5.99	5.1	6.8	0.43
FLOW	50	0.018	0	0.240	0.040
COD	25	33.7	8	99	20.2
TOC	25	12.6	3	46	8.7
TP	39	0.217	0.01	1.43	0.244
NH_3-N	8	0.176	<0.01	0.86	0.299
NO_3-N	40	0.335	<0.01	1.03	0.249
TKN	40	1.496	0.24	3.92	0.859
Cl	40	10.66	1.5	19.9	5.25
SS	14	56.0	7	404	104

Station 6

DO	49	8.85	5.2	14.4	1.86
TEMP	51	14.9	2	25	5.7
COND	49	77.0	32	410	61.2
pH	34	5.99	5.1	6.8	0.43
FLOW	52	0.121	0.0080	2.47	0.350
COD	32	20.5	<4	68	17.5
TOC	33	9.2	2	31	6.8
TP	52	0.129	0.03	0.85	0.137
NH_3-N	13	0.177	<0.01	1.15	0.390
NO_3-N	52	0.142	<0.01	1.44	0.220
TKN	52	0.996	<0.04	5.25	0.884
Cl	52	8.70	1.5	19.2	2.66
SS	19	8.4	1	25	7.2

Station 29

COD	23	26.8	8	68	13.4
TOC	24	13.0	5	34	6.7

APPENDIX (continued)

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
TP	39	0.144	0.05	0.38	0.076
NH_3-N	12	0.097	<0.01	0.57	0.161
NO_3-N	41	0.083	<0.01	0.59	0.124
TKN	41	1.316	0.28	3.23	0.796
Cl	41	8.75	3.0	25.6	3.73
SS	18	12.5	2	31	7.5

Station 7

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
DO	41	9.30	4.5	12.6	2.34
TEMP	44	14.1	4	24	6.4
COND	51	77.0	32	410	61.2
pH	29	6.08	4.6	7.5	0.65
FLOW	51	0.024	0	0.264	0.052
COD	29	28.2	8	73	14.6
TOC	29	12.8	1	45	8.6
TP	43	0.229	0.04	1.40	0.259
NH_3-N	12	0.197	<0.01	1.68	0.474
NO_3-N	45	0.564	<0.01	2.21	0.519
TKN	45	1.288	<0.04	3.90	0.916
Cl	45	10.94	3.2	22.2	4.22
SS	18	21.5	1	111	25.2

Station 8

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
DO	46	8.35	1.5	12.4	2.69
TEMP	49	14.7	4	26	6.7
COND	48	180	34	1180	233
pH	29	6.24	4.3	9.0	0.80
FLOW	51	0.011	0	0.144	0.025
COD	30	34.1	12	110	23.6
TOC	30	16.4	1	80	15.4
TP	48	0.480	0.05	2.82	0.636
NH_3-N	13	0.164	<0.01	0.61	0.190
NO_3-N	49	1.017	0.07	2.65	0.619
TKN	49	1.789	<0.04	6.38	1.259
Cl	49	19.01	3.7	72.5	15.78
SS	20	26.2	4	182	39.6

Station 9

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
DO	46	8.53	4.2	12.8	2.47
TEMP	49	14.5	4	24	6.6
COND	48	98.1	25	320	61.8

APPENDIX (continued)

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
pH	30	6.15	4.8	6.8	0.49
FLOW	52	0.209	0.000082	4.90	0.749
COD	31	27.9	6	64	14.3
TOC	31	11.7	2	25	6.5
TP	52	0.180	0.04	0.73	0.146
NH_3-N	14	0.132	<0.01	1.07	0.275
NO_3-N	52	1.062	0.05	2.54	0.654
TKN	52	1.366	<0.04	4.13	0.801
Cl	52	11.14	3.5	20.6	3.35
SS	20	27.4	6	75	17.1

Station 10

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
DO	46	7.15	1.7	13.5	3.01
TEMP	51	15.4	3	26	6.9
COND	50	86.1	30	190	38.3
pH	32	6.13	4.8	7.2	0.56
FLOW	52	0.886	0.040	12.42	1.935
COD	31	27.9	4	91	17.9
TOC	31	31.0	<1	39	9.0
TP	52	0.380	0.03	1.64	0.319
NH_3-N	14	0.192	<0.01	0.87	0.277
NO_3-N	52	0.535	0.03	1.05	0.255
TKN	52	1.389	<0.04	3.36	0.736
Cl	52	8.95	3.5	14.9	2.48
SS	20	9.6	1	28	8.7

Station 11

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
DO	16	7.32	3.7	12.1	3.17
TEMP	19	10.3	5	23	5.9
COND	18	88.8	24	380	94.2
pH	17	5.66	3.7	7.2	1.12
FLOW	48	0.0015	0	0.061	0.0087
COD	10	65.8	28	125	31.4
TOC	10	29.4	12	57	14.3
TP	17	2.951	0.06	33.22	8.085
NH_3-N	4	0.20	0.05	0.55	0.24
NO_3-N	18	0.206	0.01	0.94	0.234
TKN	17	3.129	0.84	13.50	3.609
Cl	17	14.89	2.0	49.0	12.93
SS	3	21	4	44	20

APPENDIX (continued)

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
Station 12					
DO	44	6.45	0.2	12.8	3.43
TEMP	50	13.5	3	25	6.8
COND	49	67.1	22	200	38.2
pH	28	5.91	5.1	7.6	1.27
FLOW	52	0.180	0	3.31	0.602
COD	29	41.2	19	71	13.8
TOC	28	19.1	8	36	7.5
TP	47	0.218	0.05	2.29	0.386
NH_3-N	12	0.219	<0.01	1.30	0.409
NO_3-N	47	0.048	<0.01	0.63	0.099
TKN	47	1.351	<0.04	3.36	0.778
Cl	47	6.81	1.5	11.1	2.28
SS	19	12.6	1	29	8.0
Station 13					
DO	47	7.60	1.9	12.3	2.77
TEMP	51	14.0	3	25	6.8
COND	49	59.9	25	170	24.4
pH	32	5.86	5.0	6.9	0.52
FLOW	52	0.998	0	18.54	3.368
COD	30	34.3	8	68	13.3
TOC	29	13.2	1	33	6.4
TP	47	0.129	0.05	0.33	0.071
NH_3-N	12	0.140	<0.01	1.03	0.289
NO_3-N	47	0.464	<0.01	1.46	0.341
TKN	47	1.343	<0.04	4.77	0.894
Cl	47	9.37	3.9	30.5	3.80
SS	16	15.4	2	167	40.4
Station 14					
DO	42	8.43	3.7	14.2	2.35
TEMP	47	13.4	2	22	5.9
COND	46	58.0	30	190	32.4
pH	25	5.77	4.5	6.9	0.52
FLOW	52	0.0319	0	0.28	0.0465
COD	27	25.9	8	44	11.2
TOC	27	11.4	3	23	5.6
TP	48	0.080	0.02	0.44	0.069

APPENDIX (continued)

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
NH_3-N	11	0.045	<0.01	0.18	0.067
NO_3-N	48	1.882	0.12	8.96	1.944
TKN	48	1.053	<0.04	2.80	0.517
Cl	48	8.45	2.8	12.1	1.90
SS	18	6.8	1	27	7.1
Station 15					
DO	45	8.44	4.4	14.2	2.55
TEMP	49	13.8	0.5	23	6.3
COND	47	51.6	30	110	18.1
pH	31	6.05	4.8	7.4	0.56
FLOW	52	0.120	0	2.01	0.301
COD	30	18.4	4	37	8.6
TOC	30	7.8	1	20	4.7
TP	48	0.113	0.02	0.60	0.127
NH_3-N	12	0.027	<0.01	0.09	0.029
NO_3-N	48	0.363	<0.01	1.13	0.269
TKN	48	1.043	<0.04	3.80	0.791
Cl	48	7.71	2.7	51.4	6.83
SS	18	4.7	1	28	6.1
Station 16					
DO	45	6.96	1.4	12.2	3.21
TEMP	49	13.8	1	26	7.1
COND	48	55.0	25	150	25.6
pH	31	6.02	4.9	7.2	0.54
FLOW	52	0.249	0	1.96	0.377
COD	30	30.9	10	55	11.7
TOC	31	12.9	3	28	6.1
TP	48	0.122	0.04	0.60	0.092
NH_3-N	12	0.089	<0.01	0.57	0.167
NO_3-N	48	0.084	<0.01	0.56	0.120
TKN	48	1.212	0.28	3.39	0.706
Cl	48	6.29	2.4	8.8	1.29
SS	18	9.8	1	33	9.5
Station 17					
DO	40	10.37	4.3	16.6	2.49
TEMP	41	12.3	3	23	5.6
COND	39	41.9	10	180	27.5

APPENDIX (continued)

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
pH	27	6.17	5.3	7.1	0.44
FLOW	50	0.0874	0	1.76	0.256
COD	26	26.1	4	67	14.3
TOC	26	11.7	2	30	7.1
TP	40	0.100	0.02	0.65	0.130
NH_3-N	11	0.045	<0.01	0.29	0.084
NO_3-N	42	0.019	<0.01	0.13	0.028
TKN	42	1.101	<0.04	2.80	0.666
Cl	42	3.81	1.8	9.4	1.38
SS	16	4.7	1	14	3.7

Station 18

DO	45	9.46	2.3	17.4	2.97
TEMP	46	12.8	2	22	5.7
COND	44	48.1	10	200	30.2
pH	28	6.10	5.2	7.1	0.48
FLOW	50	0.0821	0	1.71	0.248
COD	27	23.0	6	46	11.1
TOC	27	10.7	4	24	5.1
TP	44	0.082	0.02	0.74	0.107
NH_3-N	10	0.059	<0.01	0.29	0.088
NO_3-N	44	0.022	<0.01	0.15	0.028
TKN	44	1.046	<0.04	2.96	0.719
Cl	44	3.97	2.3	10.3	1.57
SS	17	4.7	1	17	4.8

Station 19

DO	48	9.18	1.7	12.8	2.92
TEMP	49	13.3	2	22	5.7
COND	47	51.5	10	200	29.9
pH	30	6.14	5.0	7.1	0.53
FLOW	52	0.219	0	3.13	0.560
COD	30	27.8	8	87	15.3
TOC	30	10.4	4	30	5.6
TP	49	0.109	0.02	0.97	0.159
NH_3-N	12	0.052	<0.01	0.29	0.082
NO_3-N	49	0.024	<0.01	0.15	0.033
TKN	49	1.078	<0.04	2.80	0.673
Cl	49	4.17	1.5	9.7	1.403
SS	20	6.2	<1	17	5.0

APPENDIX (continued)

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
Station 20					
DO	47	9.49	4.6	13.2	2.14
TEMP	49	13.7	2	24	5.7
COND	47	49.5	20	330	54.8
pH	30	6.10	5.1	7.0	0.53
FLOW	49	0.0819	0	0.99	0.165
COD	32	22.5	6	52	9.8
TOC	32	9.3	2	21	4.8
TP	51	0.119	0.02	0.74	0.114
NH_3-N	13	0.064	<0.01	0.37	0.097
NO_3-N	51	0.062	<0.01	0.24	0.048
TKN	51	1.060	<0.04	3.42	0.706
Cl	51	3.68	2.2	19.6	2.42
SS	22	11.3	<1	56	14.7
Station 22					
DO	48	9.75	5.1	14.0	2.12
TEMP	50	13.5	0.5	23	5.7
COND	48	45.9	20	150	23.8
pH	30	6.33	5.2	7.1	0.46
FLOW	49	0.201	0	1.65	0.377
COD	32	17.9	2	50	9.7
TOC	31	8.5	2	23	4.8
TP	49	0.105	0.02	0.76	0.116
NH_3-N	13	0.018	<0.01	0.06	0.020
NO_3-N	50	0.054	<0.01	0.26	0.049
TKN	49	0.999	<0.04	6.38	0.985
Cl	50	3.45	1.5	6.8	0.98
SS	22	9.6	1	66	15.8
Station 23					
DO	48	9.57	5.3	13.8	2.17
TEMP	50	13.6	0.5	24	5.8
COND	48	42.3	20	90	15.7
pH	30	6.33	5.5	6.9	0.39
FLOW	50	0.199	0	1.60	0.365
COD	32	21.2	4	73	13.9
TOC	32	8.9	1	22	5.4
TP	50	0.118	0.03	0.50	0.110
NH_3-N	13	0.025	<0.01	0.08	0.026
NO_3-N	50	0.055	<0.01	0.28	0.054

APPENDIX (continued)

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
TKN	49	1.034	<0.04	3.03	0.664
Cl	50	3.90	2.2	12.1	2.13
SS	22	10.1	1	83	18.8
Station 24					
DO	48	9.46	4.3	13.4	2.27
TEMP	50	13.7	0.5	24	5.9
COND	48	43.2	20	97	17.1
pH	30	6.41	5.5	8.2	0.52
FLOW	49	0.380	0	3.93	0.744
COD	32	20.0	4	48	8.8
TOC	32	8.6	3	21	4.5
TP	51	0.103	0.03	0.64	0.101
NH_3-N	13	0.019	<0.01	0.06	0.022
NO_3-N	51	0.058	<0.01	0.21	0.044
TKN	51	1.065	<0.04	3.35	0.764
Cl	51	4.10	2.0	20.3	2.76
SS	22	10.0	<1	76	17.3
Station 25					
DO	50	9.53	4.0	13.9	2.35
TEMP	51	13.5	1.5	23	5.9
COND	49	43.1	20	110	16.4
pH	30	6.30	5.2	7.0	0.56
FLOW	52	0.580	0	6.33	1.213
COD	33	23.4	4	76	13.9
TOC	33	8.5	1	23	4.6
TP	52	0.094	0.03	0.46	0.076
NH_3-N	13	0.027	<0.01	0.08	0.029
NO_3-N	52	0.058	<0.01	0.24	0.052
TKN	52	1.153	0.23	3.57	0.781
Cl	52	4.95	1.5	55.3	8.39
SS	22	10.7	1	88	21.8
Station 28					
COD	23	20.7	4	50	11.0
TOC	23	9.0	1	22	5.7
TP	41	0.079	0.03	0.14	0.026
NH_3-N	12	0.022	<0.01	0.06	0.022
NO_3-N	42	0.044	<0.01	0.15	0.037

APPENDIX (continued)

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
TKN	42	1.094	<0.04	4.23	0.741
Cl	42	3.48	1.6	7.3	0.96
SS	21	9.0	1	79	16.9

Station 26

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
DO	50	9.38	4.1	14.1	2.58
TEMP	52	13.4	3	24	6.2
COND	50	42.7	20	88	14.0
pH	31	6.26	5.1	7.2	0.48
FLOW	52	0.247	0	4.86	0.706
COD	32	21.5	8	40	9.0
TOC	32	9.5	1	21	4.7
TP	51	0.114	0.02	0.78	0.151
NH_3-N	14	0.029	<0.01	0.08	0.027
NO_3-N	51	0.048	<0.01	0.20	0.038
TKN	51	1.152	<0.04	3.84	0.939
Cl	51	4.61	2.0	21.1	3.39
SS	22	11.2	<1	94	20.1

Station 27

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
DO	49	9.21	2.2	13.4	2.89
TEMP	51	13.2	3	22	6.0
COND	49	50.6	25	108	20.2
pH	32	6.30	5.4	7.0	0.47
FLOW	52	0.195	0.000008	1.36	0.313
COD	32	18.1	4	39	8.9
TOC	32	6.8	1	22	4.8
TP	52	0.150	0.02	1.15	0.248
NH_3-N	14	0.023	<0.01	0.09	0.028
NO_3-N	52	0.038	<0.01	0.12	0.029
TKN	52	1.120	<0.04	4.19	0.787
Cl	52	6.07	2.0	32.0	4.41
SS	22	6.1	1	20	5.4

Station 30

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
DO	35	9.21	5.5	13.6	2.38
TEMP	37	15.7	1	26	6.3
COND	38	68.0	30	220	31.2
pH	17	6.37	5.6	7.6	0.50
FLOW	38	0.091	0	1.77	0.324

APPENDIX (continued)

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
COD	19	20.7	8	71	14.5
TOC	19	8.3	2	28	5.6
TP	38	0.108	0.04	0.34	0.072
NH_3-N	14	0.035	<0.01	0.17	0.055
NO_3-N	38	0.084	<0.01	0.87	0.151
TKN	38	1.127	0.15	3.63	0.924
Cl	38	5.08	2.6	19.2	2.67
SS	17	5.1	<1	12	3.4

Station 31

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
DO	35	9.09	6.2	13.1	2.06
TEMP	38	14.5	1	23	6.2
COND	38	42.2	20	110	17.3
pH	19	6.26	5.1	7.0	0.50
FLOW	38	0.169	0.00066	2.75	0.441
COD	19	18.7	4	75	14.9
TOC	19	6.6	1	26	5.4
TP	38	0.102	0.03	0.35	0.065
NH_3-N	14	0.021	<0.01	0.07	0.022
NO_3-N	38	0.166	<0.01	0.43	0.085
TKN	38	0.963	<0.04	2.93	0.622
Cl	38	3.51	2.1	6.9	0.969
SS	18	11.0	2	30	9.2

Station 32

Variable	Samples	Mean	Minimum	Maximum	Standard Deviation
DO	35	8.92	6.1	13.0	2.08
TEMP	38	14.6	1	24	6.5
COND	38	43.3	19	100	17.1
pH	19	6.17	4.8	6.7	0.535
FLOW	38	0.278	0.015	3.16	0.588
COD	19	13.9	4	55	10.7
TOC	19	6.1	1	31	6.5
TP	38	0.102	0.02	0.50	0.104
NH_3-N	14	0.013	<0.01	0.04	0.015
NO_3-N	38	0.082	<0.01	0.28	0.073
TKN	38	0.919	<0.04	3.73	0.730
Cl	38	4.00	2.3	29.3	4.40
SS	18	4.3	1	13	3.3